Research Article

Hermann Drewes*

Historical development of SIRGAS

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Abstract: The Geodetic Reference System for the Americas (Sistema de Referencia Geodésico para las Américas, SIRGAS) was initiated in 1993 for South America at an international conference organised 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) in Asunción, Paraguay. The corresponding South American reference network was observed in 1995 by a ten-day GPS campaign at 58 stations. The network was extended to Central and North America in 2000 and immediately afterwards converted to a frame of continuously observing GNSS stations instead of short-term campaigns. The linear station position changes (velocities) were estimated by a multi-year least squares adjustment of weekly solutions, the first being published in 2002. The total set of station velocities served for the computation of continuous surface deformation models, the first over South America was published in 2005. Today, SIRGAS is accepted by most of the American states as the official geodetic reference frame. Besides the product generation (station positions, velocities, and surface deformation), SIRGAS is active in education and training offering schools and workshops for students, surveyors, and other stakeholders.

Keywords: geocentric reference frame for South America, regional geodetic reference frame, SIRGAS, terrestrial reference frame

1 Introduction

The first International Terrestrial Reference Frame (ITRF) was the ITRF-0 with station positions for the reference epoch 1988.0 (Boucher and Altamimi 1989). At the same time, the first continental GPS campaign was organised in Western Europe in order to establish a European Reference Frame (EUREF 1992). From 1988 on, various GPS campaigns for studying the geodynamics in South America were performed in cooperation of South American with European and North American institutions, for example:

- "Central And South America" (CASA, Drewes et al. 1989, 1995, Kellogg et al. 1989, Kellogg and Dixon 1990) in Costa Rica, Panama, Colombia, Venezuela, and Ecuador;
- "South America-Nazca Plate Motion Project" (SNAPP, Norabuena et al. 1998) in Bolivia, Peru.
- "Central Andes Project" (CAP, Kendrick et al. 1999 2001) in northern Argentina and Chile.
- "South America Geodynamic Activities" (SAGA, Klotz et al. 1999) in Argentina and Chile.

In 1989, the International Association of Geodesy (IAG) and the Pan-American Institute of Geography and History (PAIGH) signed a cooperation convention, and in 1990, the PAIGH Working Group "Integration of Geodetic Networks" recommended the redefinition of the South American datum. In 1991, a symposium "Recent Geodetic and Gravimetric Research in Latin America" was held at the General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Vienna, Austria, publishing discrepancies of the various datums in Latin America, e.g., Bogotá, Campo Inchauspe, Chúa, PSAD56, SAD69 (Cadess et al. 1993).

From November 24 to December 3, 1992, the "International Conference of Cartography and Geodesy" was held in Maracaibo, Venezuela, with a forum discussion on the "Integration of the Geodetic Networks in South America." As an outcome, the Deutsches Geodätisches Forschungsinstitut (DGFI, Director H. Drewes) as one of the organizers of CASA and intermediary of SAGA proposed a joint GPS campaign for all geodynamic projects in South America (letter to the IAG President Prof. W. Torge, the President of IAG Commission X "Continental Networks" Dr. K. Poder, and the Chair of the PAIGH Working Group, Ing. E. Pallejá). In a letter of June 15, 1993, H. Drewes invited all the geodynamics projects and South American countries to participate in the joint

* **Corresponding author: Hermann Drewes,** School of Engineering and Design, Technical University of Munich, Arcisstr. 21, 80333 Munich, Germany, e-mail: h.drewes@tum.de

campaign and to initiate a South American Reference System by GPS (SIRGAS). All addressees endorsed it, proposing the start in 1994 or 1995. Consequently, the IAG President W. Torge convoked a meeting on a "Unified South American Datum" during the IAG Scientific Assembly in Beijing, China, August 10, 1993. At this meeting, two different methods for datum unification were presented: M. Kumar (DMA) proposed to connect the existing triangulation networks by GPS; H. Drewes (DGFI) suggested establishing a new continental reference frame by GPS. As a result, it was decided to convoke a respective IAG/PAIGH conference in South America.

2 The conference "Unification of the South American Datum" 1993

The IAG/PAIGH conference was held in Asunción, Paraguay, October 4–7, 1993, (Figure 1) the principal results being summarised by the following objectives:

- To define a Geocentric Reference System for South America (**SI**stema de **R**eferencia **G**eocéntrico para **A**mérica del **S**ur, SIRGAS).
- To establish and maintain a reference network of SIRGAS.
- To define and realise the geocentric datum (origin, orientation, scale).

The goals to achieve these objectives were the following:

- To reach the objectives (except the maintenance of the reference network which is a long-term task) by the year 1997 in order to present it at the IAG Scientific Assembly in Rio de Janeiro at that time.
- To promote and coordinate the efforts of each South American country.
- To concentrate at the beginning on the horizontal datum (postponing the vertical datum).
- To facilitate the connection with the existing national triangulation networks.

The general organisational structure of SIRGAS included a Committee composed of one representative from each South American country and IAG and PAIGH, a Project Bureau to be established at the Instituto Brasileiro de Geografia e Estatistica (IBGE), and a Scientific Council. The SIRGAS Committee elected Luiz Paulo Fortes, Brazil, as the SIRGAS President. Two Working Groups were formed to conduct the necessary activities for fulfilling the objectives:

- WG I "Reference System" to establish the reference frame by GPS including the existing ITRF stations and adjust it in the ITRF datum, President: Melvin Hoyer, Venezuela.
- WG II "Geocentric Datum" to connect stations of the national triangulation networks by GPS and perform a common net adjustment (like NAD83), President: Walter Subiza, Uruguay.

The two Working Groups met in separate meetings to discuss the immediate steps of activities. WG I concluded that the reference system should coincide with the definition of the IERS Terrestrial Reference System (ITRS, Boucher 1990) and the reference frame should be realized by the observation and highly precise analysis of a GPS network in connection with the ITRF. WG II decided that the continental SIRGAS reference frame should be extended to national networks including existing triangulation stations, and the geodetic datum should be consistent with the Geodetic Reference System GRS 1980 (Moritz 1980).

3 First realisation of the SIRGAS reference frame

There were several meetings of the SIRGAS Working Groups in the subsequent years for planning the realisation of the SIRGAS objectives. WG II met in Bogotá, Colombia (April 1994), and both Working Groups met in La Plata, Argentina (October 1994), (Figure 2). The main topics were the organisation of a GPS observation campaign for establishing the SIRGAS reference frame in 1995 and connecting it with the national networks. The principal outcome was as follows:

- Working Group I "Reference System"

  To select a set of about 50 stations spread over all South American countries and forming the continental reference frame. It is observed in a campaign of one to two weeks by GPS and all the observations are processed as an integrated network using scientific software. The restriction of the number of stations was mainly due to the availability of GPS receivers and the capacity of the scientific software at that time. In addition to those from South American countries, German and French institutions and DMA provided many receivers.

Figure 1: Participants of the conference "Unification of the South American Datum", Asunción, Paraguay, October 4–7, 1993.

- Working Group II

  To connect a number of selected stations of the existing national triangulation networks by GPS and process it in a common adjustment of GPS and triangulation data. There were approximately 800 stations expected. However, Working Group II never organised an observing campaign connecting triangulation points of different countries, but several triangulation points were included in the continental reference frame organised by Working Group I.

The GPS observation campaign for the establishment of the continental reference frame was practised by a test campaign in 1994 within a project of the International GNSS Service (IGS), which started its activities in 1994. After this experience, all participating South American countries proposed a number of stations for the SIRGAS reference frame according to their geographic surface. Finally, 58 sites in 11 countries were accepted including seven IGS stations in South America plus Easter Island in the Pacific and O'Higgins in Antarctica. The observation campaign was executed over 10 days from May 26, 0:00 UT to June 4, 24:00 UT. The station occupation had to be organised precisely in a detailed observation plan, because there were not sufficient receivers to occupy all the stations simultaneously, and there were four types with different antennas without internationally accepted calibration. Thus, various sites had to be observed by different receivers, some of them simultaneously at eccentric points (Figure 3).

The GPS data were analysed by two analysis centres, DGFI and NIMA (National Imagery and Mapping Agency as the successor of DMA, today National Geospatial-Intelligence Agency, NGA). The results were discussed at the meeting of SIRGAS WG I in Isla Margarita, Venezuela, in April 1997. There was a problem with the antenna phase centres of the different receiver types, because the Bernese 3.4 software (Hugentobler et al. 2001) used by DGFI permitted phase centre corrections, while GIPSY-OASIS II (Webb and Zumberge 1997) used by NIMA did not permit those corrections. The decision was to separate the NIMA network according to the receiver types and perform similarity transformations to the four DGFI partial networks. The geocentric reference was realised by fixing the coordinates of the nine IGS stations with the ITRF1994 values. The DGFI

Figure 2: Opening session and Working Group discussion at the SIRGAS meeting, La Plata, Argentina, 1994.

Figure 3: SIRGAS 1995 reference frame with four employed receiver types.

and NIMA receiver-type solutions were combined to the final solution using the station occupations with different receivers. The precision extends from ±3 mm to ±6 mm for the X, Y, and Z coordinates in the ITRF1994. The results are published in the SIRGAS Final Report (1997).

SIRGAS is included in the IAG structure for the first time in the period 1995–1999 in Section I "Positioning" (The Geodesist's Handbook 1996). The results of the observation campaign 1995 were presented at the IAG Scientific Assembly 1997 in Rio de Janeiro, Brazil. There were 12 presentations published in the IAG Symposia Series (Forsberg et al. 1998).

In 1996, the IGS established Regional Network Associate Analysis Centres (RNAAC) for processing continental networks as densifications of the global IGS reference frame. The RNAAC for South America was identified as the SIRGAS analysis centre and allocated to DGFI as IGS RNAAC SIRGAS. Consequently, SIRGAS forms an official part of the IGS. The IGS RNAAC SIRGAS is regularly computing weekly station coordinates of all SIRGAS stations and periodically accumulating multi-year solutions with position coordinates at a reference epoch and station velocities.

3.1 Establishment of a reference system for physical heights

During a business meeting at the IAG General Assembly 1997, the SIRGAS Committee decided to create a Working Group III "Vertical Datum" with the objective to establish a vertical reference for all South American countries and connect all the levelling networks to one vertical datum. Roberto Teixeira Luz, Brazil, was elected as its president. The first SIRGAS WG III meeting was held in August 1998 in Santiago de Chile (Figure 4). There were general discussions on the types of heights (orthometric, normal, dynamic, and ellipsoidal), the inclusion of the existing levelling networks, and the datum of the vertical reference system (reference point, tide gauges, sea level, etc.). The initial recommendation was to introduce normal heights in all South American countries. This recommendation was revised in 2000 by the decision to adjust the levelling networks in geopotential numbers, with the option to derive normal, orthometric, or any other type according to the decision of each country. The countries were urged to readjust the levellings with gravity corrections.

3.2 SIRGAS repetition in 2000, expansion to The Americas and conversion to continuous observations

The GPS campaign 1995 was repeated in 2000 during the same period of the year (May 10–19) in order to avoid systematic seasonal effects. Another objective was to extend the network to the Caribbean and Central and North America (Figure 5). Three centres did the data processing and the network adjustment (Drewes et al. 2005):

Figure 4: Participants of the SIRGAS WG III meeting, Santiago de Chile, August 1998.

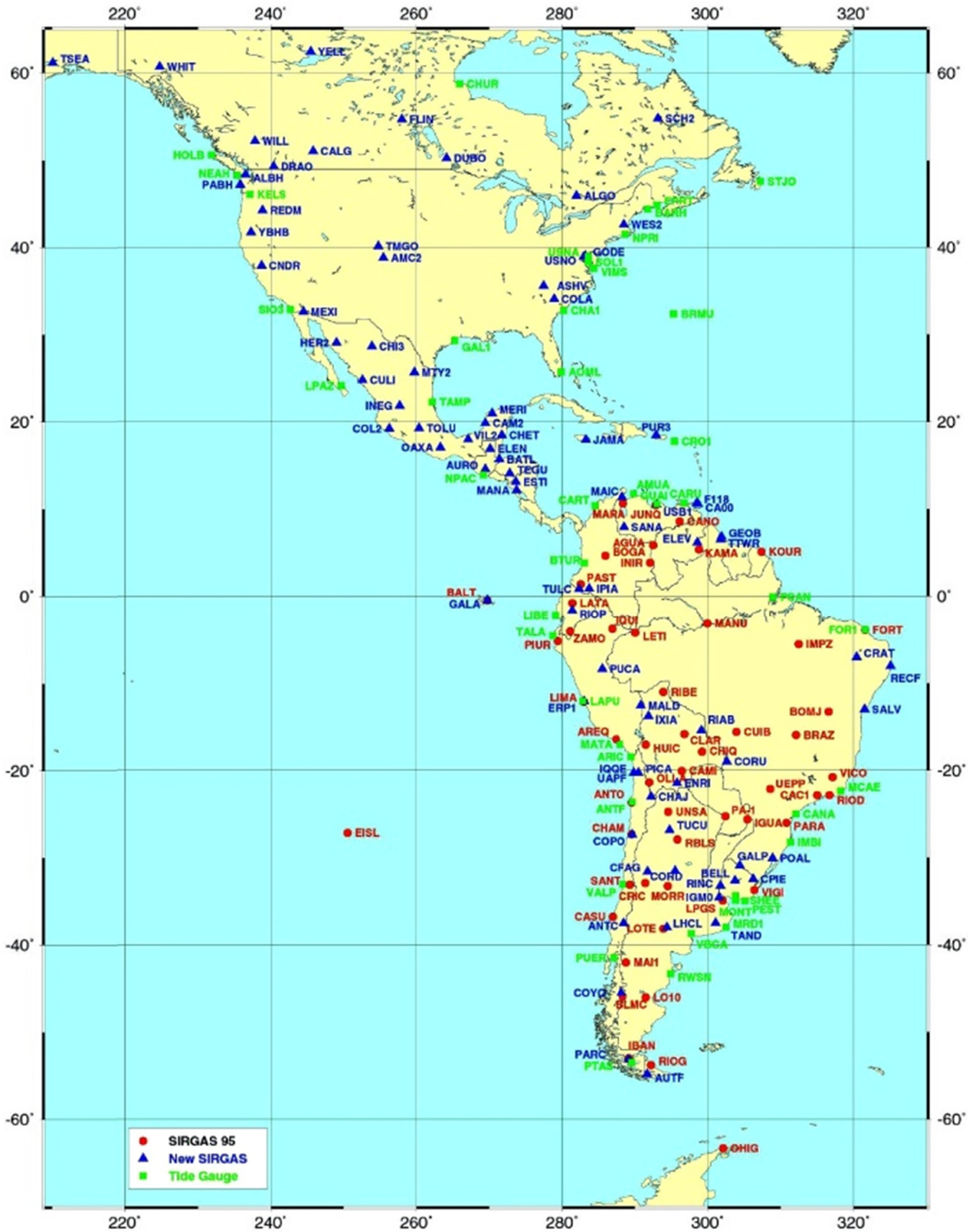

Figure 5: Extension of SIRGAS to the Caribbean and Central and North America.

DGFI (Germany), IBGE (Brazil), and the Bavarian Geodetic Commission (BEK, Germany). The precision of the coordinates of 184 stations resulted in an average of ±1.3 mm for X and Z, and ±2.5 mm for Y (i.e. mainly in heights).

Due to the extension of the network, the name changed to Geocentric Reference System for the Americas, **Si**stema de **R**eferencia **G**eocéntrico para las **A**mérica**S.** This extension was affirmed by the resolution of the Seventh United

Nations Regional Cartographic Conference for the Americas in January 2001 with the recommendation that all member countries of the Americas integrate their national geodetic reference systems into a reference system compatible with SIRGAS.

In the same year 2000, DGFI started computing kinematic solutions of station coordinates at a fixed epoch and linear station position changes (velocities) from continuous observations over several years (multi-year solutions). A complete list is given by Sánchez et al. 2022 (this issue). Table 1 presents a selected list of the multi-year solutions demonstrating the tremendous increase of stations. A comparison of the solution DGFI02P01 (Seemüller et al. 2002) with the differences of the SIRGAS campaigns 1995 and 2000 (Figure 6) shows a very good agreement confirming the precision of the SIRGAS

Table 1: Selected multi-year SIRGAS station position and velocity solutions computed by DGFI

Name	Aligned to	Time span	Stations	References
DGFI00P01	ITRF97	1996-06-30 through 2000-02-27	31	Seemüller et al. 2002
DGFI01P02	ITRF2000	1996-06-30 through 2001-10-20	49	Seemüller and Drewes 2004
DGFI06P01	ITRF2000	1996-06-30 through 2006-06-17	94	Seemüller 2009
SIR11P01	ITRF2008	2000-01-02 through 2011-04-16	230	Sánchez and Seitz 2011
SIR14P01	IGb08	2010-04-18 through 2014-07-26	242	Sánchez 2015
SIR15P01	IGb08	2010-03-14 through 2015-04-11	303	Sánchez and Drewes 2016
SIR17P01	IGS14	2011-04-17 through 2017-01-28	345	Sánchez and Drewes 2020

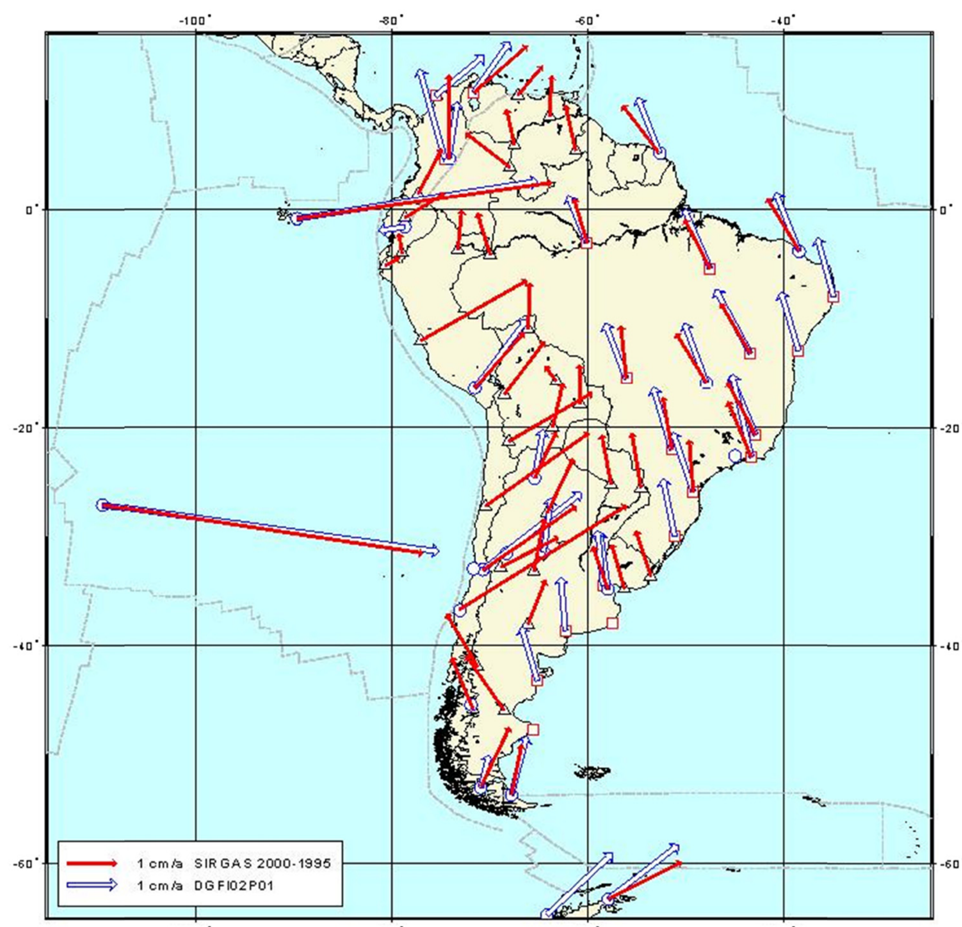

Figure 6: Comparison of SIRGAS2000–SIRGAS1995 differences and the DGFI multi-year solution.

campaigns. Figure 7 presents for comparison the multi-year solution 2015, which shows in an emphatic way the increase of the number of stations and the effect of the Maule earthquake in Chile 2010 (Sánchez and Drewes 2016).

3.3 Continuous surface velocity models of South America (VEMOS)

The SIRGAS multi-year solutions form (together with the geodynamic projects CASA, SNAPP, CAP, and SAGA) the initiative for the continuous surface velocity models of South America (VEMOS). The first model (VEMOS2003, Drewes and Heidbach 2005) was computed by two different methods: a geodetic least squares collocation approach (LSC) and the geophysical finite element method (FEM). The input data are given by 329 velocities derived from continuously observing GPS stations and several GPS geodynamics projects. The different data sets were transformed to a common kinematic datum by deriving the rotation vector of the South American plate from station motions of the IGS Regional Network (IGS RNAAC SIRGAS) in the rigid eastern part and reducing these plate motions from all the data sets. The resulting residual motions define the

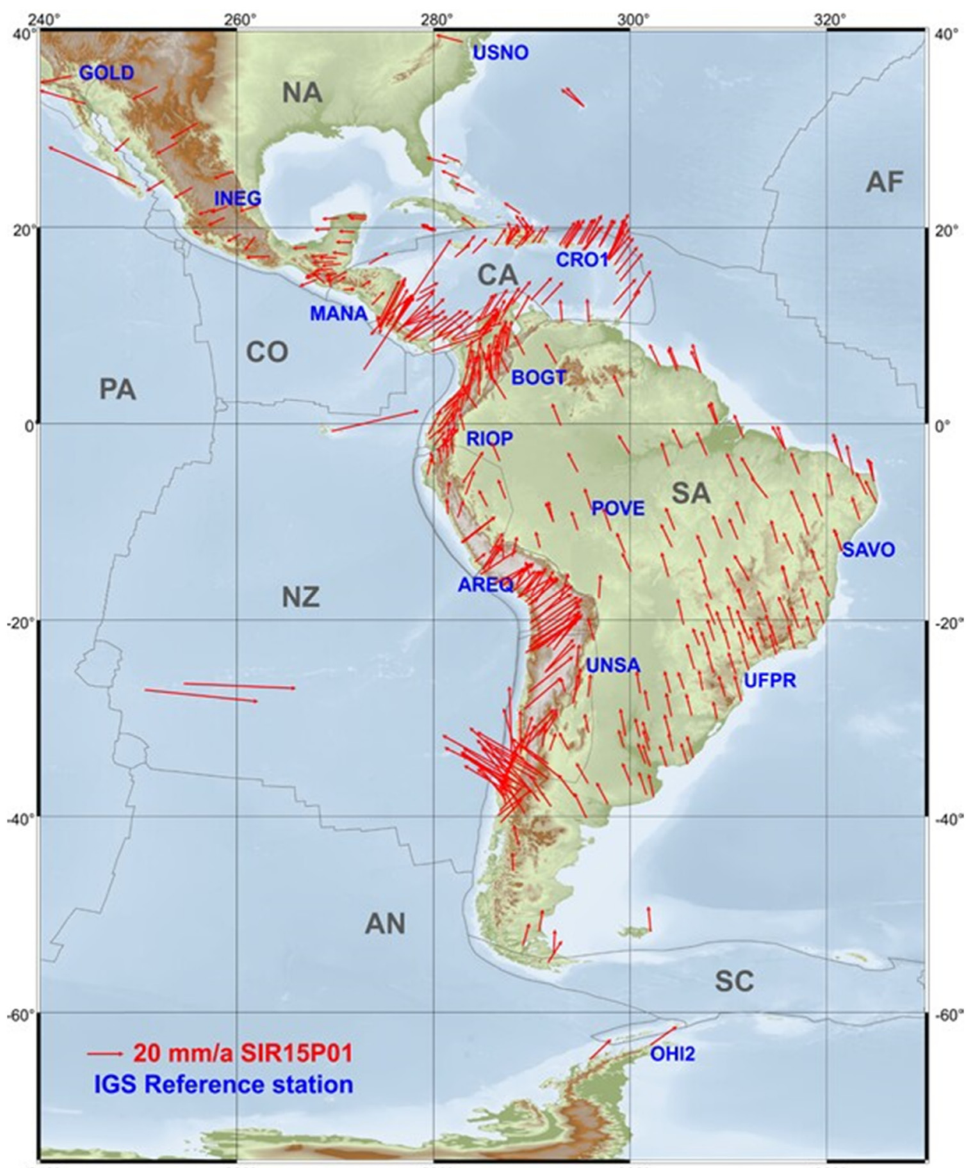

Figure 7: Station velocities from the SIRGAS multi-year solution SIR15P01 (2010-03-14 through 2015-04-11).

boundary conditions in the FEM and the input signals in the LSC. For the FEM, a network of approximately 75,000 linear elements was generated. The model rheology is a homogeneous elastic material (Young's modulus 70 GPa and Poisson ratio 0.3). For the LSC, empirical covariance functions are derived from the observed velocity vectors. The comparison of both methods shows an agreement in the mm/a level. The result is a continuous surface velocity model for the South American continent (Figure 8).

The velocity models for SIRGAS (VEMOS) are computed periodically, in particular when strong seismic events have produced significant changes in the station movements. Such an event was the Maule earthquake 2010 when a dramatic change in the station velocities was observed. Figure 9 shows the velocities in the Maule region before (2000.0–2009.6), 2–5 years after (2012.3–2015.2), and 4–7 years after the earthquake (2014.0–2017.1). The changing direction of the movements is obvious, in particular in the southern region.

4 Conclusion

SIRGAS has developed from an international scientific project on the definition and establishment of a South American geocentric reference frame to an international organisation

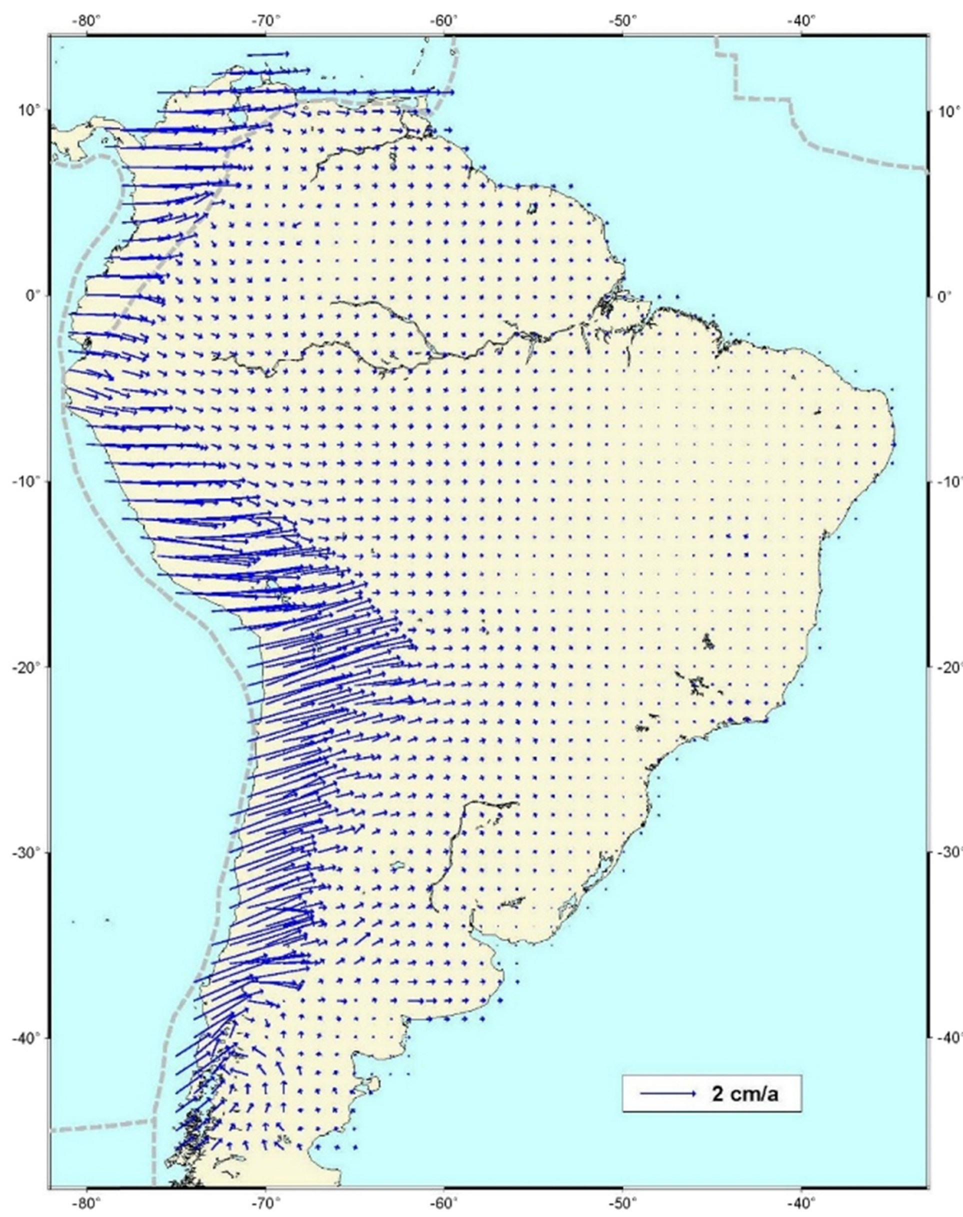

Figure 8: Velocity model for South America (VEMOS2003) relative to the rigid South American plate.

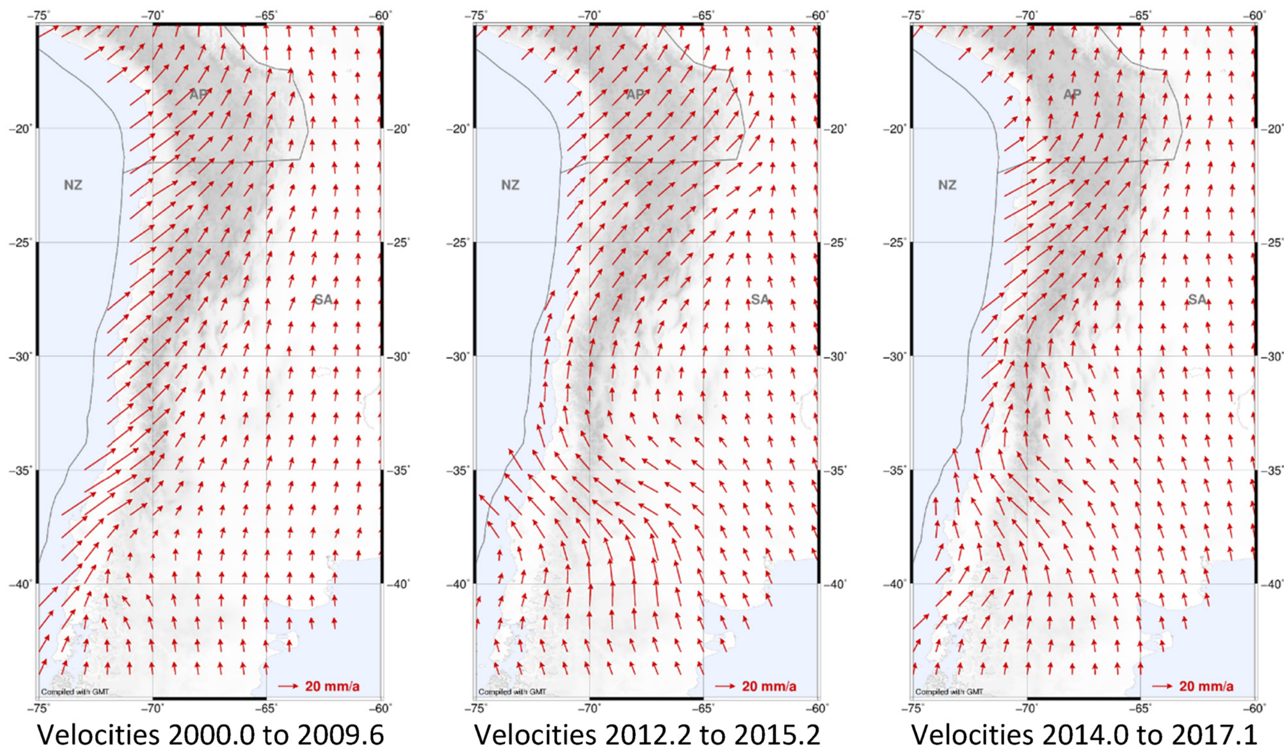

Figure 9: Changing surface deformation from VEMOS2009, 2015, and 2017 (Sánchez and Drewes 2020).

providing fundamentals for scientific research and products for geodesy and surveying. The SIRGAS products (time-dependent station coordinates, station velocities, and surface deformations) are used in science and practice. Besides these products, SIRGAS is organising symposia (https://sirgas.ipgh.org/en/sirgas-events/symposia/), schools for students (https://sirgas.ipgh.org/en/sirgas-events/schools/) and workshops on various topics (https://sirgas.ipgh.org/en/sirgas-events/traninig/). In this way, SIRGAS is an internationally prestigious organisation, which may serve as an example for other continents. The organisational issues may be found at the SIRGAS Homepage (https://sirgas.ipgh.org); the processing of the SIRGAS continuously operating network on a weekly basis and in terms of multi-year solutions within the IGS RNAAC-SIRGAS is available at the corresponding Homepage (https://www.sirgas.org).

Conflict of interest: Author states no conflict of interest.

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