Improved Analysis Strategy and Accessibility of the SIRGAS Reference Frame

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Abstract

The SIRGAS reference system is at present realized by the SIRGAS Continuously Operating Network (SIRGAS-CON) composed by about 200 stations distributed over Latin America and the Caribbean. SIRGAS member countries are improving their national reference frames by installing continuously operating GPS stations, which have to be consistently integrated into the continental network. As the number of these stations is rapidly increasing, the analysis strategy of the SIRGAS-CON network is based on two hierarchy levels: a) A core network with homogeneous continental coverage and stable site locations ensures the long-term stability of the reference frame. This network is processed by DGFI (Germany) as the IGS RNAAC SIR. b) Several densification sub-networks (corresponding to the national reference networks) improve the accessibility to the reference frame in the individual countries. Currently, the SIRGAS-CON stations are classified in three densification sub-networks (a southern, a middle, and a northern one), which are processed by the SIRGAS Local Processing Centres CIMA (Argentina), IBGE (Brazil), and IGAC (Colombia). These four Processing Centres deliver loosely constrained weekly solutions for the assigned sub-networks, which are integrated in a unified solution by the SIRGAS Combination Centres (DGFI and IBGE). The main SIRGAS products are: loosely constrained weekly solutions in SINEX format for further combinations of the

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network, weekly positions aligned to the ITRF as reference for GPS positioning in Latin America; and multi-year solutions (positions + velocities) for practical and scientific applications requiring time-dependent coordinates. This paper describes the analysis of the SIRGAS-CON network as the current realization of the SIRGAS reference system, its quality and consistency, as well as the planned activities to continue improving this reference frame.

1.1 Introduction

SIRGAS (Sistema de Referencia Geocéntrico para las Américas) as a reference system is defined identical with the ITRS (International Terrestrial Reference System). It is realized by means of a regional densification of the global ITRF (International Terrestrial Reference Frame) in Latin America and the Caribbean. The SIRGAS reference frame is in the same way extended to the countries through national densifications, which provide accessibility to the reference frame at national and local levels (Sanchez and Brunini 2009). SIRGAS has three realizations: two by means of episodic GPS campaigns and one by means of a network of continuously operating GPS stations. The first realization of SIRGAS (SIRGAS95) refers to the ITRF94, epoch 1995.4. It is given by a high-precision GPS network of 58 points distributed over South America (SIRGAS, 1997). In 2000, this network was re-measured and extended to the Caribbean, Central and North American countries. This second realization (SIRGAS2000) includes 184 GPS stations and refers to the ITRF2000, epoch 2000.4 (Drewes et al. 2005). The third realization of SIRGAS is the SIRGAS Continuously Operating Network (SIRGAS-CON), which is at present composed by more than 200 permanently operating GPS sites. The SIRGAS-CON network is weekly computed by the SIRGAS Analysis Centres; main products of this computation are: loosely constrained weekly solutions for station positions to be included in the IGS (International GNSS Service) global polyhedron and in multi-year solutions of the network; weekly station positions aligned to the ITRF for further applications in Latin America; and multi-year solutions providing station positions and velocities for high-precise practical and scientific applications. The SIRGAS-CON weekly positions refer to the observation epoch and to the current frame in which the GPS satellite orbits (i.e. IGS final orbits, Dow et al. 2009) are given, at present the IGS05, the IGS realization of the ITRF2005 (see IGSMAIL 5447, http://igscb.jpl.nasa.gov/). The coordinates of the multi-year solutions refer to the latest available ITRF and to a specified epoch, e.g. the most recent SIRGAS-CON multi-year solution SIR09P01 refers to IGS05, epoch 2005.0 (Seemuller et al. 2009). The relationship between the different SIRGAS realizations is given by the transformation parameters between the corresponding ITRF solutions they refer and by taking into account the station position variations with time through a velocity (deformation) model (Drewes and Heidbach 2005). In this way, realizations or densifications of SIRGAS associated to different ITRFs and reference epochs materialize the same reference system and, after reducing them to the same frame and epoch, their positions are compatible at the mm-level.

The present paper summarizes the improvement of the SIRGAS realization by means of the SIRGAS-CON network, the applied procedures for generating weekly solutions of this reference frame, quality and consistency of the obtained coordinates, as well as ongoing activities to avoid some disadvantages of the actual analysis strategy. The multi-year solutions for the SIRGAS-CON reference frame are presented by e.g. Seemuller et al. 2008, 2009.

1.2 The SIRGAS-CON Reference Frame

The initial realizations of SIRGAS based on pillars have been replaced by an increasing number of continuously operating GPS stations (Fig. 1.1), which all together constitute the SIRGAS-CON network (Fig. 1.2). 48 of these stations belong to the IGS global network, while the others (about 160) correspond to the national reference frames.

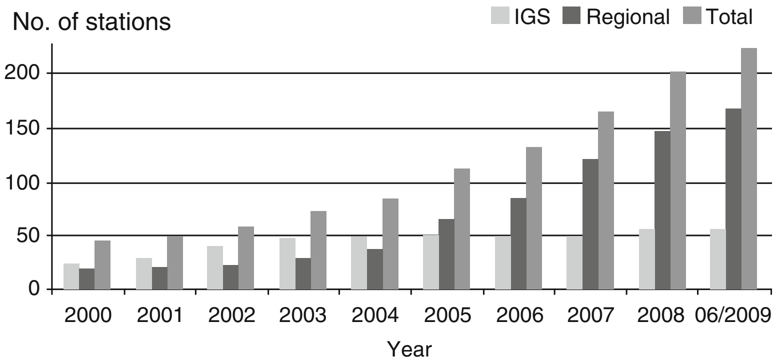

Fig. 1.1 SIRGAS continuously operating stations since 2000

To guarantee the consistency of the national reference frames with the global reference frame in which the GPS orbits are computed, the national reference stations are integrated into the SIRGAS-CON network and all together are processed in a common way. This provides homogeneous consistency and accuracy of their coordinates on a continental level. Until GPS week 1495 (August 2008), the Deutsches Geodätisches Forschungsinstitut (DGFI, Germany), as the IGS RNAAC SIR (IGS Regional Network Associate Analysis Centre for SIRGAS), processed the entire SIRGAS-CON network in one block only (Seemuller and Drewes 2008). However, given the large number of SIRGAS-CON stations, this usual one-block processing became unfeasible and it was necessary to re-define the analysis strategy of the network. The new analysis strategy is based on (1) defining a core continental network (SIRGAS-CON-C) as the primary densification of the ITRF in Latin America, and (2) improving the geographical density of this core network by means of densification sub-networks (SIRGAS-CON-D). The core network ensures the long-term stability of the continental reference frame, while the densification sub-networks make it available at national and local levels. Although, they appear as two different categories, core and densification stations match requirements, characteristics, performance, and quality of the ITRF stations.

The SIRGAS-CON-D sub-networks shall correspond to the national reference frames, i.e., as an optimum there shall be as many sub-networks as countries in the region. Since at present not all of the countries are operating a Processing Centre, the existing stations are classified in three densification sub-networks (Fig. 1.2): a northern one covering Mexico, Central America, the Caribbean, Colombia, and Venezuela; a middle one comprising stations installed on Brazil, Ecuador, Bolivia, Suriname, French Guyana, Guyana, Peru, and Bolivia; and a southern one including the stations located in Uruguay, Paraguay, Argentina, Chile, and Antarctica. Each densification sub-network includes a minimum number of IGS and SIRGAS-CON core stations as overlapping points for the combination.

1.3 Analysis of the SIRGAS-CON Network

The SIRGAS-CON-C network is computed by DGFI. The densification sub-networks are processed by the active SIRGAS Local Processing Centres until new ones become operational. At present, they are: Centro de Procesamiento Ingeniería-Mendoza-Argentina at the Universidad Nacional del Cuyo (CIMA, Argentina), Instituto Brasileiro de Geografia e Estatistica (IBGE, Brazil), and Instituto Geográfico Agustín Codazzi (IGAC, Colombia). These four Processing Centres apply a common procedure established by SIRGAS (in agreement with the standards of the IGS and the IERS – International Earth Rotation and Reference Systems Service) to generate loosely constrained weekly solutions for station positions (see e.g. Natali et al. 2009; Seemuller and Sanchez 2009). In these solutions satellite orbits, satellite clock offsets, and Earth orientation parameters are fixed to the final weekly IGS solutions (Dow et al. 2009) and all station positions are constrained to ±1 m.

The individual contributions are integrated in a unified solution by the SIRGAS Combination Centres DGFI and IBGE (Fig. 1.3). The DGFI combinations are provided to the users as the SIRGAS official

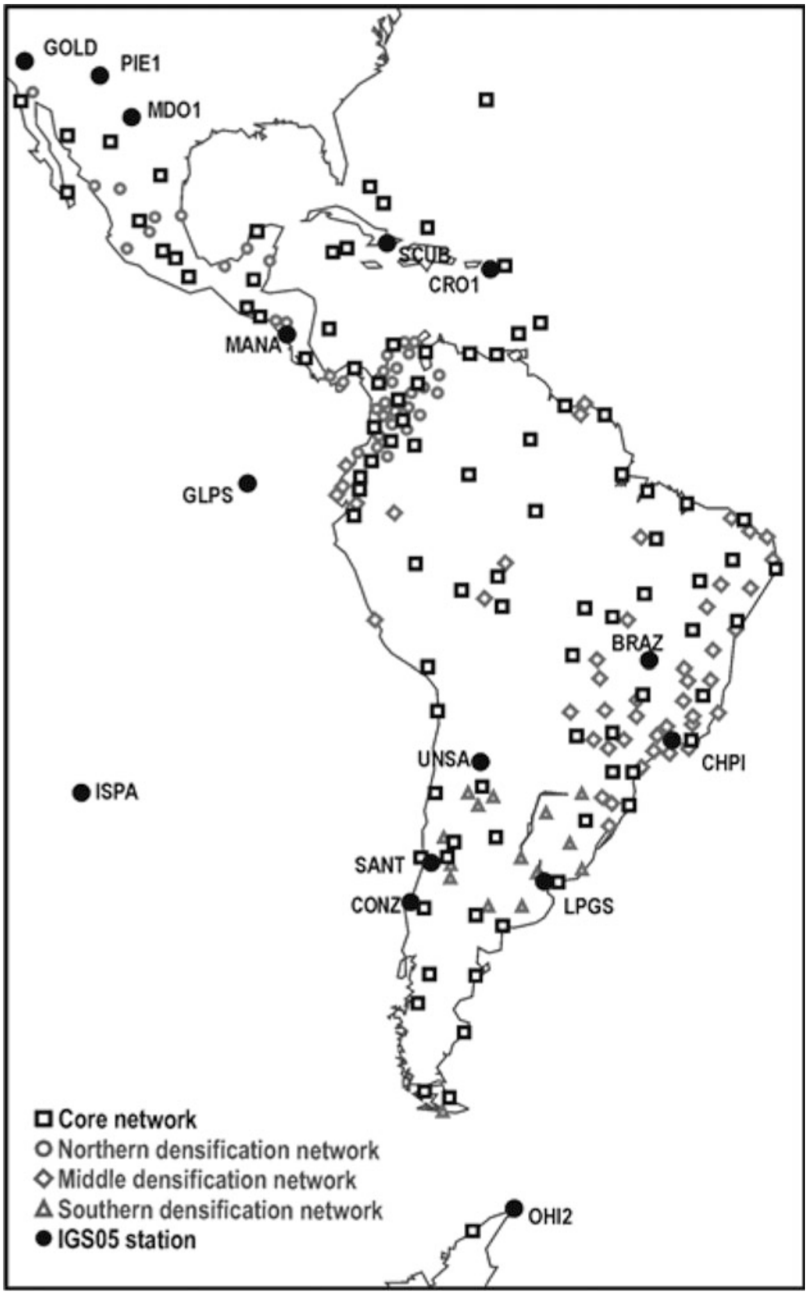

Fig. 1.2 SIRGAS-CON network (status August 2009)

products (Sanchez et al. 2011), while the IBGE combinations assure redundancy and control for those products (Costa et al. 2009). At present, all SIRGAS Analysis Centres use the Bernese GPS Software (Dach et al. 2007) for processing the individual sub-networks and for their combination.

Before combining the individual solutions, the constraints included in the delivered normal equations are removed and the solutions are separately aligned to the IGS05 reference frame. The obtained standard deviations are analysed to establish the quality of the individual solutions and to determine variance factors, when it is necessary to compensate differences in the stochastic models of the Processing Centres. The station positions computed from each solution are compared by means of a similarity transformation to the

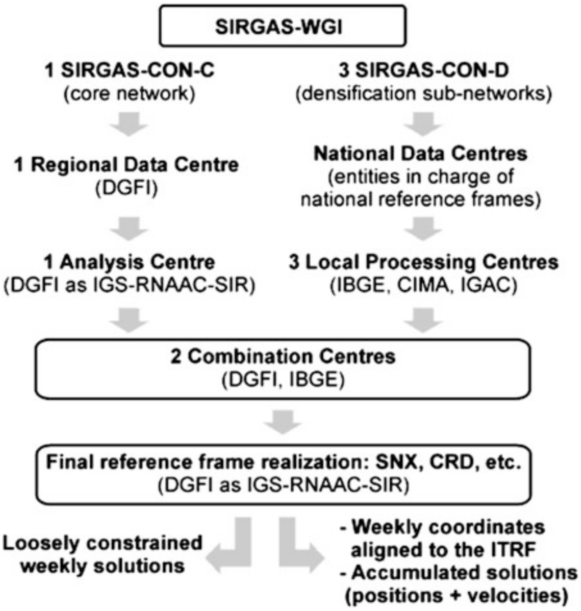

Fig. 1.3 Data flow in the weekly processing of the SIRGAS-CON reference frame

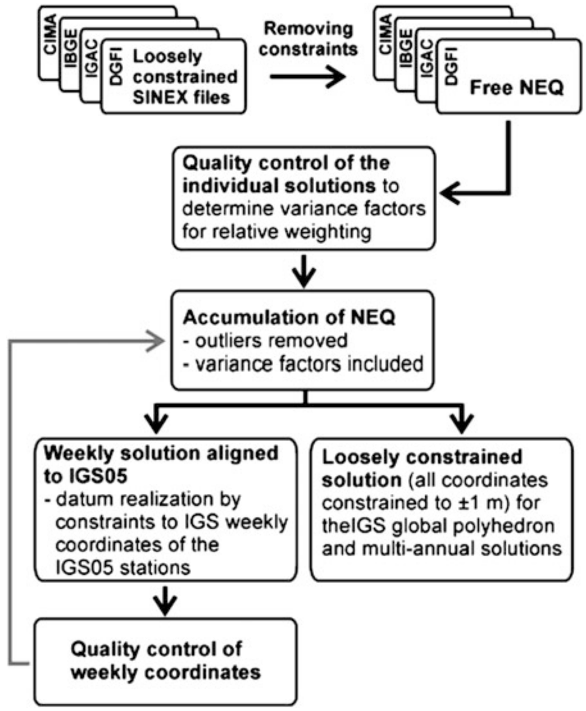

Fig. 1.4 Combination procedure applied to generate the weekly solution of the SIRGAS-CON reference frame

IGS weekly values and to each other to identify possible outliers. Once inconsistencies and outliers are reduced from the individual free normal equations, a combination for a loosely constrained weekly solution for station positions (all of them constrained to ±1 m) is computed. This solution is submitted in SINEX format to IGS for the global polyhedron and it is stored to be included in the next multi-year solution of the SIRGAS-CON network. A solution aligned to the IGS05 reference frame is also computed to provide weekly positions of all SIRGAS-CON stations for further applications (Fig. 1.4).

Different criteria are applied to establish the quality of the contributing solutions delivered by the SIRGAS Processing Centres. The first one relates to the determination of mean standard deviation of station positions by solving the individual normal equations with respect to the IGS05 frame. These standard deviations represent the formal errors of the individual solutions. Secondly, the analysis of station position time series allows ascertaining the consistency of the individual contributions from week to week (repeatability). Then, the comparison by means of a similarity transformation of the individual solutions referring to the IGS05 with the IGS weekly positions provides information about their compatibility with the IGS global network. Figure 1.5 presents the mean values for each criterion and for each sub-network for the period between the GPS weeks 1495 and 1538. These results indicate that the individual solutions are at the same level of precision: the formal error of the station positions is about ±1.6 mm and the repeatability of the weekly coordinates is estimated to be ~ ±2.0 mm for the horizontal component and ±4.0 mm in the height.

1.4 Weekly Processing of the SIRGAS-CON Reference Frame

Regional and national reference frames supporting GNSS positioning must be consistent with the reference frame in which the GPS orbits are determined. For that reason, the IGS RNAAC SIR yearly generates a new multi-year solution referred to the current ITRF realization and including the SIRGAS-CON stations operating more than 2 years (e.g. Seemuller et al 2008, 2009). The latest solution SIR09P01 contains 128 stations with positions and velocities referring to IGS05, epoch 2005.0 (Seemuller et al. 2009). However, as mentioned before, the SIRGAS-CON network

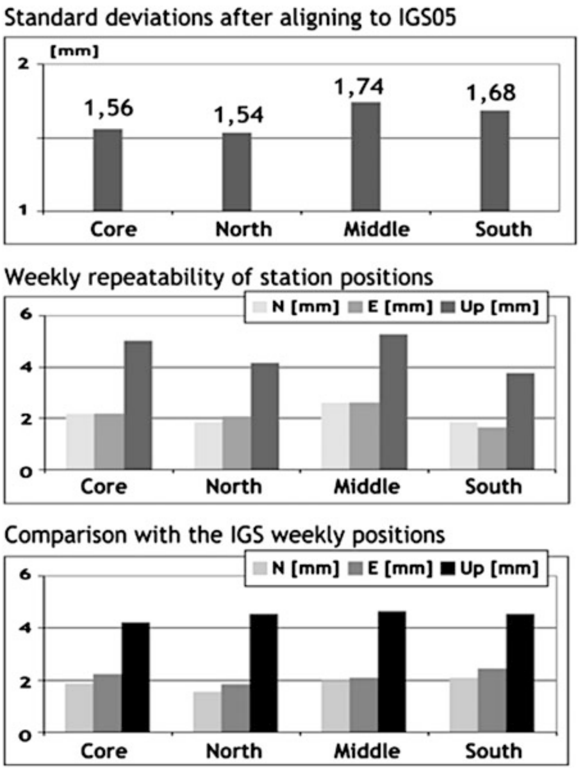

Fig. 1.5 Evaluation of the solutions computed for the SIRGAS-CON individual sub-networks (mean values for the period GPS weeks 1495–1538)

is composed by more than 200 stations and those stations (about 80) that are not included in SIR09P01 can be used as reference points only, if their weekly positions linked to the ITRF (i.e. IGS05) are available. In this way, weekly solutions of the SIRGAS-CON network aligned to the IGS05 frame are necessary.

Usually, epoch solutions (daily, weekly, multi-year) of regional reference networks are aligned to the ITRF using a set of fiducial stations with known positions and constant velocities; i.e. they consider linear coordinate changes only. However, GPS stations show significant seasonal position variations (mainly in the up component) resulting from a combination of geophysical loading and systematic errors. Ignoring these seasonal variations at reference stations can introduce systematic errors in the datum realization and the reference networks can be significantly deformed. These effects are larger in regional networks than in global ones, especially in zones with strong seasonal variations as the SIRGAS region. In this way, with the objective of minimizing the influence of seasonal variations in the weekly realization of the SIRGAS-CON frame, the SIRGAS Working Group I (Reference System) analyzed different strategies for the datum definition taken into account the minimal network deformation, the weekly repeatability of station positions, and the consistency with the IGS weekly solutions for the global network. This analysis basically consisted of solving the same free normal equations applying two different sets of reference coordinates for the datum definition: the first one corresponds to the IGS05 positions at epoch 2000.0 extrapolated to the observation epoch using the ITRF2005 constant velocities. The second set corresponds to the weekly positions determined for the IGS05 reference stations within the IGS weekly combination (igs*yy*P*wwww*.snx).

After comparing the loosely constrained solutions (in which the network is not deformed) with the constrained ones, the main conclusion shows that applying constant velocities to the reference coordinates introduces the largest distortions (more than 5 mm) into the station positions, mainly at the fiducial points (Fig. 1.6). This is a consequence of constraining a seasonal signal to be a linear trend. In this way, the SIRGAS-CON weekly solutions are aligned to the IGS05 by constraining the positions of the reference IGS05 stations to the values resulting of the IGS weekly combinations (Sanchez et al. 2011).

The quality control of the SIRGAS-CON weekly solutions takes into account (1) the mean standard deviation for station positions to estimate the formal error of the final values; (2) the coordinate repeatability after combining the individual solutions to evaluate the internal consistency of the combined network; (3) station position time series analysis to determine the consistency of the combined solutions from week to week; and the (4) comparison with the IGS weekly coordinates and the IBGE weekly combinations to ascertain the reliability of the weekly solutions as well as to guarantee the required redundancy for the generation of the final SIRGAS-CON weekly positions. Table 1.1 summarizes the mean values resulting from the evaluation criteria for the period covering the GPS weeks 1495–1538. The mean standard deviation of the combined solutions is very similar to those obtained for the individual contributions (Fig. 1.5), i.e. their quality is maintained and their combination does not generate distortions in the SIRGAS-CON weekly realization. The weekly repeatability of the resulting

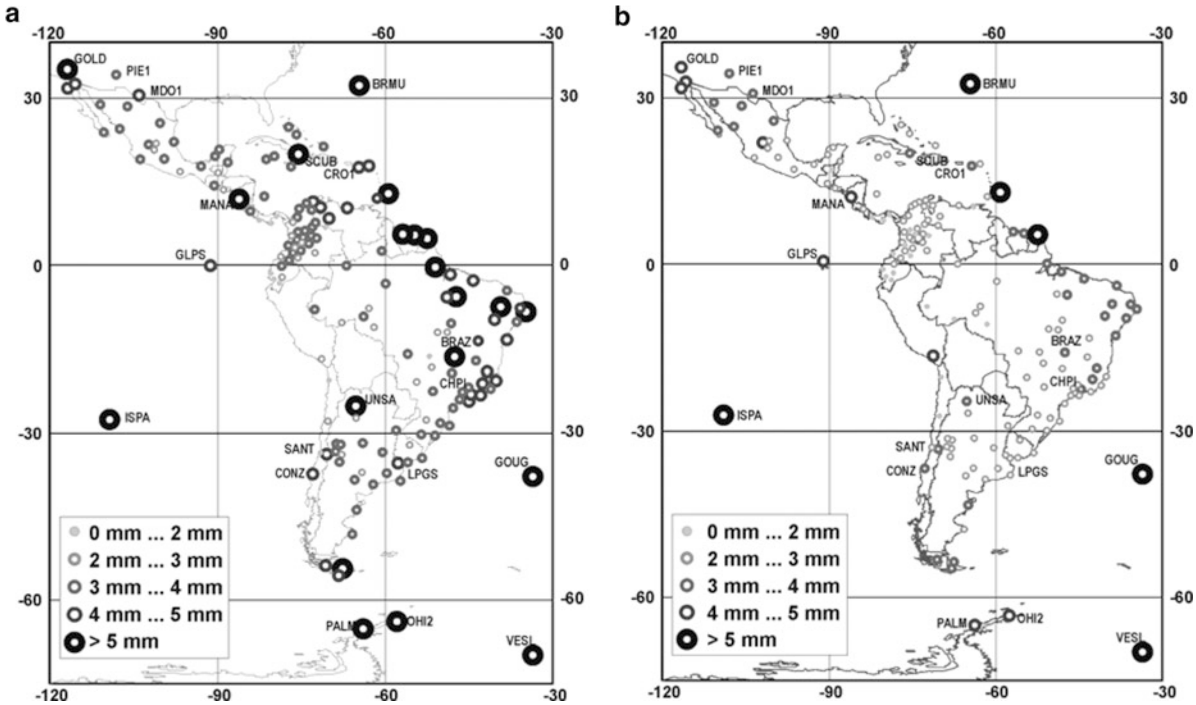

Fig. 1.6 3D residuals derived after comparing the primary loosely constrained solutions for the SIRGAS-CON network with the same solutions aligned to the IGS05 frame applying two different sets of reference coordinates for the datum definition. In (**a**) the IGS05 station positions at 2000.0 are extrapolated to the observation epoch by means of the ITRF2005 constant velocities. In (**b**) the station positions computed within the IGS weekly combinations for the IGS05 stations are directly introduced as reference coordinates. Values presented on the maps are mean values for 117 weeks

Table 1.1 Evaluation of the SIRGAS-CON weekly realizations (mean values for the period between GPS weeks 1495–1538)

Criteria	Component	Value in [mm]
Mean standard deviation		1.64
Mean RMS of residuals for coordinate repeatability in the weekly combination	N	0.61
	E	0.87
	Up	2.51
	Total	2.73
Mean RMS of residuals derived from time series of station positions	N	1.50
	E	1.36
	Up	3.80
	Total	4.33
RMS of residuals wrt IGS weekly solutions	N	1.39
	E	1.75
	Up	3.69
	Total	4.35
RMS of station coordinate differences between DGFI and IBGE combinations	N	1.10
	E	1.10
	Up	1.40
	Total	2.20

positions provides an estimate of the internal consistency of approximately ±0.8 mm in the horizontal components and ±2.5 mm in the vertical one. The RMS values derived from the time series for station coordinates and with respect to the IGS weekly positions indicate that the external accuracy of the network is about ±1.5 mm in the horizontal position and ±3.8 mm in the height.

1.5 Closing Remarks and Outlook

The processing strategy described in this paper for the SIRGAS-CON network is applied since GPS week 1495. As already mentioned, before (since June 1996 to August 2008), the entire SIRGAS-CON network was computed by DGFI in one adjustment. In order to establish the consistency of the current combined solutions with the previous computations, residual position time series were generated from the weekly solutions available between January 2000 and January 2009. Discontinuities or jumps at the epoch in which the analysis strategy was changed (last week of August 2008) are not identifiable. Results show that the current weekly combined solutions are at the same accuracy level and totally consistent with the previous computations (when the network was calculated in one block).

Nevertheless, the present sub-network distribution has two main disadvantages: (1) Not all SIRGAS-CON stations are included in the same number of individual solutions, i.e., they are unequally weighted in the weekly combinations, and (2) since there are not enough Local Processing Centres, the required redundancy (each station processed by at least three processing centres) is not fulfilled. Therefore, SIRGAS promotes the installation of more Local Processing Centres hosted by Latin American countries. In this frame, institutions interested to install a SIRGAS Processing Centre shall pass a test period of one year. In this period, they have to align their processing strategies with the SIRGAS guidelines and meet the delivering deadlines. At present, there are five Experimental Processing Centres: Instituto Geográfico Militar of Ecuador (IGM, Ecuador), Laboratorio de Geodesia Física y Satelital at the Universidad del Zulia (LGFS-LUZ, Venezuela), Servicio Geográfico Militar of Uruguay (SGM, Uruguay), Instituto Nacional de Estadística y Geografía (INEGI, Mexico), and Instituto Geográfico Nacional de Argentina (IGN, Argentina). They will become Official Processing Centres in the near future and a redistribution of the SIRGAS-CON stations between the operative SIRGAS Analysis Centres will allow including each regional station in the same number of individual solutions. This will significantly improve the reliability and quality control of the weekly solutions for the SIRGAS-CON reference frame.

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