
Combination of the Weekly Solutions Delivered by the SIRGAS Processing Centres for the SIRGAS-CON Reference Frame

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Abstract

The SIRGAS reference frame is given by more than 200 continuously operating stations (SIRGAS-CON network), which are classified in four sub-networks: a continental one (SIRGAS-CON-C) with about 100 stations homogeneously distributed over Latin America and the Caribbean, and three densification sub-networks (SIRGAS-CON-D) covering the northern part, the middle part, and the southern part of the SIRGAS region. Each sub-network is processed by one of the SIRGAS Processing Centres: DGFI (Germany) is responsible for the SIRGAS-CON-C network, IGAC (Colombia) for the northern densification sub-network, IBGE (Brazil) for the middle one, and CIMA (Argentina) for the southern one. These Processing Centres deliver loosely constrained weekly solutions, which are integrated in a unified solution by the SIRGAS Combination Centres operating at DGFI and IBGE. The DGFI (i.e. IGS RNAAC SIR) weekly combinations are delivered to the IGS Data Centres for the global polyhedron, and are made available for users as official SIRGAS weekly reference frame solution. The IBGE weekly combinations provide control and redundancy. This paper describes the combination strategy applied by DGFI, emphasizing the evaluation of the individual solutions and the quality control of the final weekly combinations. The reliability of the resulting coordinates is estimated by comparing them with those produced by IBGE and the weekly combinations of the IGS global network.

106.1 Introduction

The densification of the ITRF in Latin America and the Caribbean is the SIRGAS Continuously Operating Network (SIRGAS-CON). This network comprises two hierarchy levels (Brunini and Sánchez 2008):

core stations (SIRGAS-CON-C) providing the primary link to the global ITRF; and densification stations (SIRGAS-CON-D) containing all the fundamental GNSS sites of the national reference frames. The densification stations are further classified in three sub-networks covering the northern part, the middle part, and southern part of the SIRGAS region (Fig. 106.1).

The core network ensures the long-term stability of the continental reference frame. The densification sub-networks improve the geographical density of the reference stations facilitating the accessibility to the reference frame in national and local levels.

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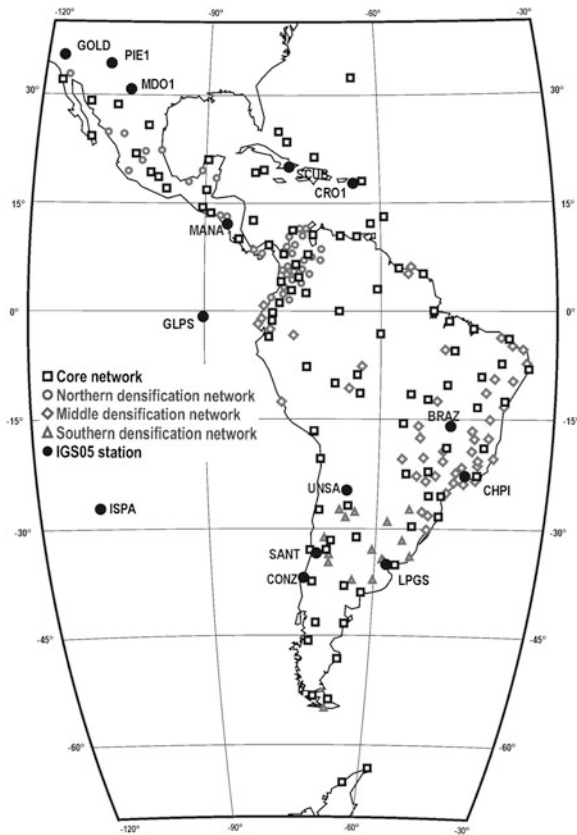


Fig. 106.1 Core and densification sub-networks of the SIRGAS-CON reference frame

This operational infrastructure is possible thanks to the active participation of many Latin American and Caribbean institutions, who not only make available the measurements of their stations, but also are hosting SIRGAS Analysis Centres in charge of processing the observational data on a routine basis.

As responsible for the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR), DGFI delivers loosely constrained weekly solutions for the SIRGAS-CON network to the IGS. These solutions are combined together with those generated by the other IGS Analysis Centres to form the IGS polyhedron (Seemüller and Drewes 2008). The processing of the SIRGAS-CON network in the frame of the IGS RNAAC SIR also includes the computation of weekly position solutions aligned to the current ITRF and accumulative position and velocity solutions for estimating the kinematics of the network (e.g. Seemüller 2009; Seemüller et al. 2009). Until GPS week 1,495, DGFI processed the entire SIRGAS-CON

network. Afterwards, with the introduction of the core and densification sub-networks, as well as the installation of SIRGAS Processing Centres in Latin American institutions, DGFI is now responsible for (1) processing the SIRGAS-CON-C core network, (2) combining this core network with the densification sub-networks, and (3) making available the final SIRGAS products (i.e. loosely constrained weekly solutions, weekly station positions referred to the ITRF, and multi-annual solutions providing station positions at a reference epoch and the corresponding velocities). This paper summarizes the activities carried out by DGFI as SIRGAS Combination Centre.

106.2 DGFI Combination Strategy

The SIRGAS Processing Centres (Table 106.1) deliver loosely constrained weekly solutions for the assigned SIRGAS-CON sub-networks. In these solutions, satellite orbits, satellite clock offsets, and Earth orientation parameters are fixed to the final weekly IGS values, and positions for all sites are constrained to ± 1 m. These individual contributions are integrated in a unified solution by the SIRGAS Combination Centres: DGFI and IBGE. The combination strategy applied by DGFI is:

1. Individual solutions are corrected for possible format problems, station inconsistencies, utilization of erroneous equipment, etc.
2. Constraints included in the delivered normal equations are removed
3. Sub-networks are separately aligned to the IGS05 reference frame by applying the no net rotation (NNR) and no net translation (NNT) conditions. The reference values are the positions of the IGS05 stations included in the corresponding IGS weekly combination, i.e. files `igsyyPwww.snX` (yy = year, www = GPS week)
4. Positions obtained in (3) for each individual solution are compared to the IGS weekly values and to each other to identify possible outliers
5. Stations with large residuals (more than ± 10 mm in the north or east components, and more than ± 20 mm in the height) are reduced from the corresponding normal equations. Steps (3), (4), and (5) are iterative
6. Variances obtained in the final computation of (3) are analyzed to estimate variance factors for

Table 106.1 SIRGAS Processing Centres and their solutions evaluated in this study

Id	Processing centre	First week	Latest week	Sub-network	No. stations
SIRGAS official processing centres					
CIM	Centro de Procesamiento Ingeniería-Mendoza-Argentina at the Universidad Nacional del Cuyo (CIMA, Argentina)	1,495	1,538	Southern sub-network	50
DGF	Deutsches Geodätisches Forschungsinstitut (DGFI, Germany)	1,495	1,538	Core network	107
IBG	Instituto Brasileiro de Geografia e Estatística (IBGE, Brazil)	1,495	1,538	Middle sub-network	94
IGA	Instituto Geográfico Agustín Codazzi (IGAC, Colombia)	1,495	1,538	Northern sub-network	94
SIRGAS experimental processing centres					
ECU	Instituto Geográfico Militar of Ecuador (IGM, Ecuador)	1,513	1,538	Selected stations northern and middle sub-networks	31
LUZ	Laboratorio de Geodesia Física y Satelital at the Universidad del Zulia (LGFS-LUZ, Venezuela)	1,520	1,538	Northern sub-network	94
URY	Servicio Geográfico Militar of Uruguay (SGM, Uruguay)	1,526	1,538	Selected stations southern and middle sub-networks	44

relative weighting of the individual solutions (see Sect. 106.4.1)

7. Once inconsistencies and outliers are reduced from the individual free normal equations, these equations are accumulated for a loosely constrained weekly combination, in which all station positions are constrained to ± 1 m. This combination is submitted to IGS for the global polyhedron and is stored to be included in the next multi-year solution of the network
8. Finally, a weekly solution aligned to the IGS05 frame is computed. The geodetic datum is defined by constraining the coordinates of the IGS05 reference stations (Fig. 106.1) to their positions computed within the IGS weekly combinations (igsyyP_{www}.snx). To minimize network distortions, the reference coordinates are introduced with a weight inversely proportional to $\pm 1E-04$ m. This solution provides the final weekly positions for the SIRGAS-CON stations
9. The accumulation and solution of the normal equations are carried out with the Bernese GPS Software V.5.0 (Dach et al. 2007)

Resulting products are (available at <http://www.sirgas.org>):

SIR_{www}7.SNX: SINEX file for the loosely constrained weekly combination.

SIR_{www}7.SUM: Report of weekly combination.

siryP_{www}.snx: SINEX file for the constrained weekly combination.

siryP_{www}.crd: Final SIRGAS-CON positions for week *www*.

Before the weekly combinations computed by DGFI for the SIRGAS-CON network are published or made available for users, a quality control is carried out to guarantee consistency and reliability of the SIRGAS products. This quality control is described in Sect. 106.4 of this paper.

106.3 Evaluation of the SIRGAS Experimental Processing Centres

SIRGAS promotes the installation of more Processing Centres hosted by Latin American institutions. Motivations for this are (Brunini et al. 2011):

1. SIRGAS member countries are qualifying their national reference frames by installing an increasing number of continuously operating GNSS stations and each country shall be able to process the data of its own stations
2. Since there are not enough Local Processing Centres, the required redundancy in the analysis of the SIRGAS-CON network is not fulfilled: not all SIRGAS-CON stations are included in the same number of individual solutions and they are unequally weighted in the weekly combinations. As an optimum, each SIRGAS-CON station shall be processed by the same number of Processing Centres (at least three)

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. DGFI as a SIRGAS Combination Centre is also responsible for evaluating the weekly solutions generated by the so-called SIRGAS Experimental Processing Centres. This evaluation includes not only the analysis of accuracy and compatibility of the individual solutions with the official SIRGAS products, but also the revision of administrative issues such as meeting deadlines, observance of the SIRGAS guidelines, accordance with the log files information, etc. The evaluation of the solutions produced by the SIRGAS Experimental Processing Centres is carried out applying the same procedure used for the SIRGAS Official Processing Centres. Details of evaluation and results are presented in the following.

106.4 Quality Control of the SIRGAS-CON Network Weekly Combinations

The generation of the weekly SIRGAS-CON products (i.e. loosely constrained combinations and station positions aligned to IGS05) includes a quality control at two levels: Firstly, the individual solutions delivered by the Processing Centres (official and experimental) are analysed to establish their quality and consistency. Once the individual solutions are reviewed and free of inconsistencies, their combination is carried out by applying the procedure summarized in Sect. 106.2. Then, the second quality control concentrates on the results of this combination. Here, the main objective is to ascertain the accuracy and reliability of the weekly solutions for the entire SIRGAS-CON network. It should be mentioned that the DGFI combinations made available for users include the solutions provided by the SIRGAS Official Processing Centres only. Combinations including solutions delivered by the Experimental Processing Centres are for internal control. In order to present the actual status of all Processing Centres, the procedures, analysis, and conclusions contained in this paper are based on all the weekly solutions summarized in Table 106.1.

106.4.1 Evaluation of Individual Solutions

Identification of outliers: To avoid deformations in the combined network, those stations with very large outliers are reduced from the weekly normal equations.

In this step, the individual loosely constrained weekly solutions are separately aligned to the IGS05 reference frame. Then, time series of weekly solutions are generated for each station included in each individual solution. In this way, if one station is processed by three Processing Centres, there will be three different time series available for the same station. By comparing the time series amongst one to another, it is easier to identify outliers and their possible causes: if outliers, jumps, or interruptions are identifiable in the different series, the problems may be specifically associated to the station (tracking deficiencies, equipment changes, failure of the data submission, earthquakes, etc.). If outliers, jumps, or interruptions are not present in all time series, the deficiencies may be associated to administrative issues of the Processing Centres (neglecting of stations, incomplete download of RINEX files, disagreement with the log files, etc.). After comparing the individual solutions, differences exceeding five times the mean RMS values derived from the position time series (i.e. $N = (5 \times 2)$ mm, $E = (5 \times 2)$ mm, $H = (5 \times 4)$ mm) are assumed as outliers, and the corresponding station(s) is reduced from the respective individual solution(s) before combination.

Quality control of the individual solutions: The relative weighting of individual solutions by means of variance factors is necessary to compensate possible differences in the stochastic models of the Processing Centres. To validate these models, we compare mean standard deviations of coordinates (obtained from solving the individual normal equations) with mean RMS values derived from the time series of station positions. The latter ones reflect the precision of the weekly position solutions. If the relation between the individual standard deviations is the same as the relation between the RMS values derived from the time series, the stochastic models are compatible and it is not necessary to apply relative weighting factors. To ensure that the RMS values are not dominated by individual stations that are not included in all solutions, they are computed in two different ways (Sánchez et al. 2008):

- (a) Evaluation of the time series of station positions per Processing Centre to ascertain the consistency of the individual solutions from week to week (i.e. weekly repeatability)
- (b) Comparison of the individual solutions with the weekly IGS positions (igsyyPwww.snx) to validate their compatibility with the IGS global network

Table 106.2 Variance factors (with respect to DGF values, i.e. SIRGAS-CON-C core network) for the individual normal equations generated by each SIRGAS Processing Centre

Processing centre/component	Approach	Variance factors						
		(a) RMS residuals for weekly repeatability (mm)	(b) RMS residuals wrt IGS weekly solutions (mm)	(c) Mean standard deviation (mm)	(a)	(b)	Mean of a, b	(c)
CIM	N	1.9	2.1					
	E	1.6	2.4					
	Up	3.8	4.6					
	Total	4.7	5.7	1.7	1.3	0.9	1.1	0.9
DGF	N	2.2	1.9					
	E	2.2	2.2					
	Up	5.0	4.2					
	Total	6.1	5.2	1.6	1.0	1.0	1.0	1.0
IBG	N	2.6	2.0					
	E	2.6	2.1					
	Up	5.3	4.7					
	Total	6.8	5.6	1.7	0.9	0.9	0.9	0.9
IGA	N	1.9	1.6					
	E	2.1	1.9					
	Up	4.2	4.5					
	Total	5.2	5.2	1.5	1.2	1.0	1.1	1.0
ECU	N	1.5	2.0					
	E	1.4	2.0					
	Up	4.1	4.8					
	Total	4.7	5.7	1.4	1.3	1.1	1.0	0.9
LUZ	N	1.4	1.6					
	E	1.5	2.0					
	Up	3.5	4.7					
	Total	4.6	5.4	1.6	1.3	1.0	1.1	1.0
URY	N	1.6	1.4					
	E	1.2	1.3					
	Up	3.6	2.9					
	Total	4.5	5.1	1.3	1.4	1.2	1.1	1.0

Complementary, the mean standard deviations (item c in Table 106.2) are determined after solving the individual normal equation with respect to the IGS05 reference frame by means of minimum datum conditions (NNR and NNT). They represent the formal errors of the individual solutions.

Table 106.2 summarizes the mean values for the described approaches over the total analysed period (Table 106.1 shows the number of GPS weeks included per Processing Centre). The variance factors are calculated with respect to the DGF values, since they correspond to the major SIRGAS-CON-C core network. In general, the variance factors derived from the different RMS values (criteria a, b) are very similar and can be

averaged. These mean values are then compared with the variance factors derived from the standard deviations (item c). They agree quite well. Consequently, and keeping in mind that all the Processing Centres are applying the same analysis strategy (double differences), the same software (Bernese), the same satellite orbits, satellite clock offsets, and Earth orientation parameters (final IGS products), as well as the same observations for the common stations (RINEX files with sampling rate of 30 s), we conclude that the parameters estimated by each of the contributing solutions are at the same precision level (i.e. there are no differences in the stochastic models) and a relative weighting of the Processing Centres is not necessary.

106.4.2 Evaluation of Combined Solutions

The weekly combined solutions for the SIRGAS-CON network are aligned to the IGS05 reference frame by constraining the positions of the IGS05 stations (Fig. 106.1) to the coordinates obtained within the IGS weekly combinations (see Sect. 106.2). The quality evaluation of these combined solutions is based on the following criteria:

- Mean standard deviation for station positions after aligning the network to the IGS05 reference frame indicates the formal error of the final combination
- The weekly repeatability of station positions after combining the individual solutions provides information about the internal consistency of the combined network
- Time series analysis for station positions allows to determine the compatibility of the combined solutions from week to week
- Comparison with the IGS weekly coordinates indicates the consistency with the IGS network
- Comparison with the IBGE weekly combination (ibgyyPwww.snX) fulfils the required redundancy to generate the final SIRGAS products. This comparison is carried out directly with the station positions (no 7-parameter similarity transformation is applied here)

Figure 106.2 presents mean values of the different applied criteria for the period covering the GPS weeks 1,495–1,538. The mean standard deviation of the combined solutions agrees quite well with those computed for the individual contributions (Table 106.2), i.e. the quality of the individual solutions is maintained and their combination does not deform or damage the internal consistency of the entire SIRGAS-CON network. The position repeatability in the weekly

combinations indicates that the internal consistency of the SIRGAS-CON network is about ± 0.8 mm in the horizontal components and about ± 2.5 mm in the vertical one. The RMS values derived from the station position time series and with respect to the IGS weekly coordinates indicate that the accuracy of the weekly positions for the SIRGAS-CON stations is about ± 1.5 mm in the North and the East, and ± 3.8 mm in the height.

The differences with respect to the IBGE combinations are about ± 1 mm for the three components (N, E, Up). Although, these differences are within the accuracy level of the weekly solutions, they are a bit larger, considering that DGFI and IBGE apply the same input normal equations for combination. This can be a consequence of the different combination strategies, especially the methodology used for the datum realization. A description about the IBGE combination procedure is given by Costa et al. (2009).

106.4.3 Correction of the Stochastic Model of the Combined Solutions

The individual solutions contributing to the final combination of the SIRGAS-CON network include common stations and they are therefore highly correlated. In spite of this, they are initially treated as independent within the combination. The omission of that correlation conduces to an overestimation of the standard deviations by a factor of about the square root of the number of individual solutions including each station. To compensate this overestimation, the standard deviations have to be multiplied by this factor and the variance-covariance matrix by the square of the

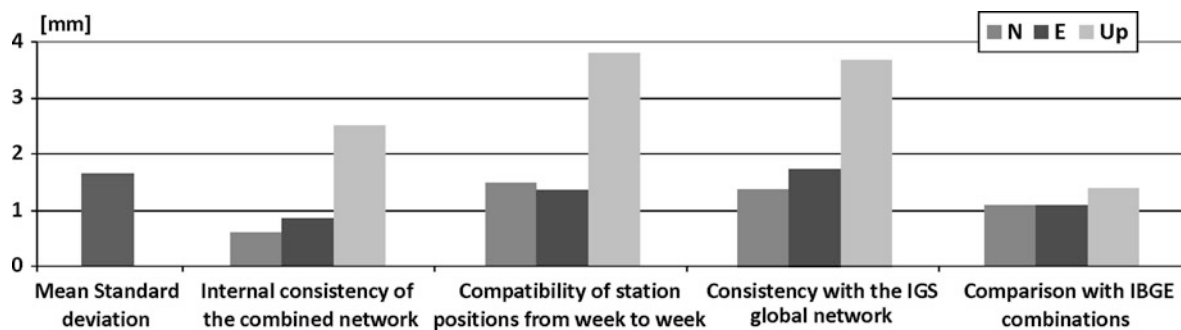


Fig. 106.2 Evaluation of the weekly positions computed for the SIRGAS-CON stations

factor. If each station is included in exactly the same number of individual solutions, this procedure can easily be carried out. However, due to different causes, the station distribution between the SIRGAS Processing Centres is not homogeneous, i.e. not all stations are included in the same number of individual solutions. It implies that the stochastic model of the combined solution cannot be corrected by one (unique) factor. It is necessary to determine separately correction factors for the stations, depending on the number of individual solutions including them. At present, we are trying to implement a method to compute and apply these factors directly in the combination software. In the mean time, it is not possible and therefore, this study does not take into account corrections for the stochastic model of the combined solutions. A good alternative to avoid this procedure is to guarantee that each regional station is included in exactly the same number of individual solutions. For that, a redistribution of the stations between the different SIRGAS Processing Centres would be necessary.

Conclusions

DGFI as a SIRGAS Combination Centre reviews, evaluates, and combines on a weekly basis the individual solutions delivered by the SIRGAS Analysis Centres: four Official Processing Centres (CIM, DGF, IBG, IGA) and three Experimental Processing Centres (ECU, LUZ, URY). The weekly solutions for the SIRGAS reference frame (i.e. loosely constrained weekly solutions and weekly station positions aligned to the IGS05) released by DGFI include the contributions of the Official Processing Centres only. Analyses containing solutions provided by the Experimental Processing Centres are for internal control. After analysing the individual solutions delivered for the period covered between the GPS weeks 1,495 and 1,538, the results permit to conclude that all SIRGAS Processing Centres (official and experimental) satisfy the administrative and quality requirements

defined in the SIRGAS guidelines. Their weekly solutions are at the same precision level with respect to each other and with respect to the weekly combinations. In general, the precision (internal consistency) of results is about ± 0.8 mm for the horizontal position and ± 2.5 mm for the vertical one, while the realization accuracy with respect to the IGS05 frame (reliability) is about ± 1.5 mm for the horizontal components and ± 3.8 mm for the height.

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