IGS Regional Network Associate Analysis Center for SIRGAS (IGS RNAAC SIR)

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1 The SIRGAS reference frame

The realisation of SIRGAS (Sistema de Referencia Geocéntrico para las Américas) is a regional densification of the International Terrestrial Reference Frame (ITRF) (e.g., SIRGAS (1997), Drewes et al. (2005), Sanchez and Brunini (2009)). At present, it is composed of GNSS stations only; other geodetic space techniques like VLBI, SLR or DORIS are not involved yet. To guarantee the appropriate maintenance of the reference frame, SIRGAS comprises (Fig. 1):

- One core network (SIRGAS–C) composed of a set of geographically well–distributed and consistently reliable reference stations. The main objective of the SIRGAS–C network is to ensure the long–term stability of the reference frame, and it is understood as the primary densification of the ITRF in Latin America and the Caribbean.
- National reference networks (SIRGAS–N) realising densifications of the core network. The central purpose of these densifications is to provide accessibility to the reference frame at national and local levels and to facilitate its extension by assimilating new reference stations (mainly those installed by the national agencies responsible for the local reference networks).

The SIRGAS reference frame is calculated weekly. The SIRGAS–C network is processed by the Deutsches Geodätisches Forschungsinstitut (DGFI, Germany) since this institute acts as the IGS Regional Network Associate Analysis center for SIRGAS (IGS RNAAC SIR, Sanchez (2012), (2013)). The SIRGAS–N networks are computed by the SIRGAS Local Processing centers, which operate under the responsibility of national Latin American organisations. At present, the SIRGAS Local Processing centers are: CEPGE (Ecuador), CPAGS–LUZ (Venezuela), IBGE (Brazil), IGAC (Colombia), IGM–Cl (Chile), IGN–Ar (Argentina), INEGI (Mexico), and SGM–Uy (Uruguay). These processing centers deliver

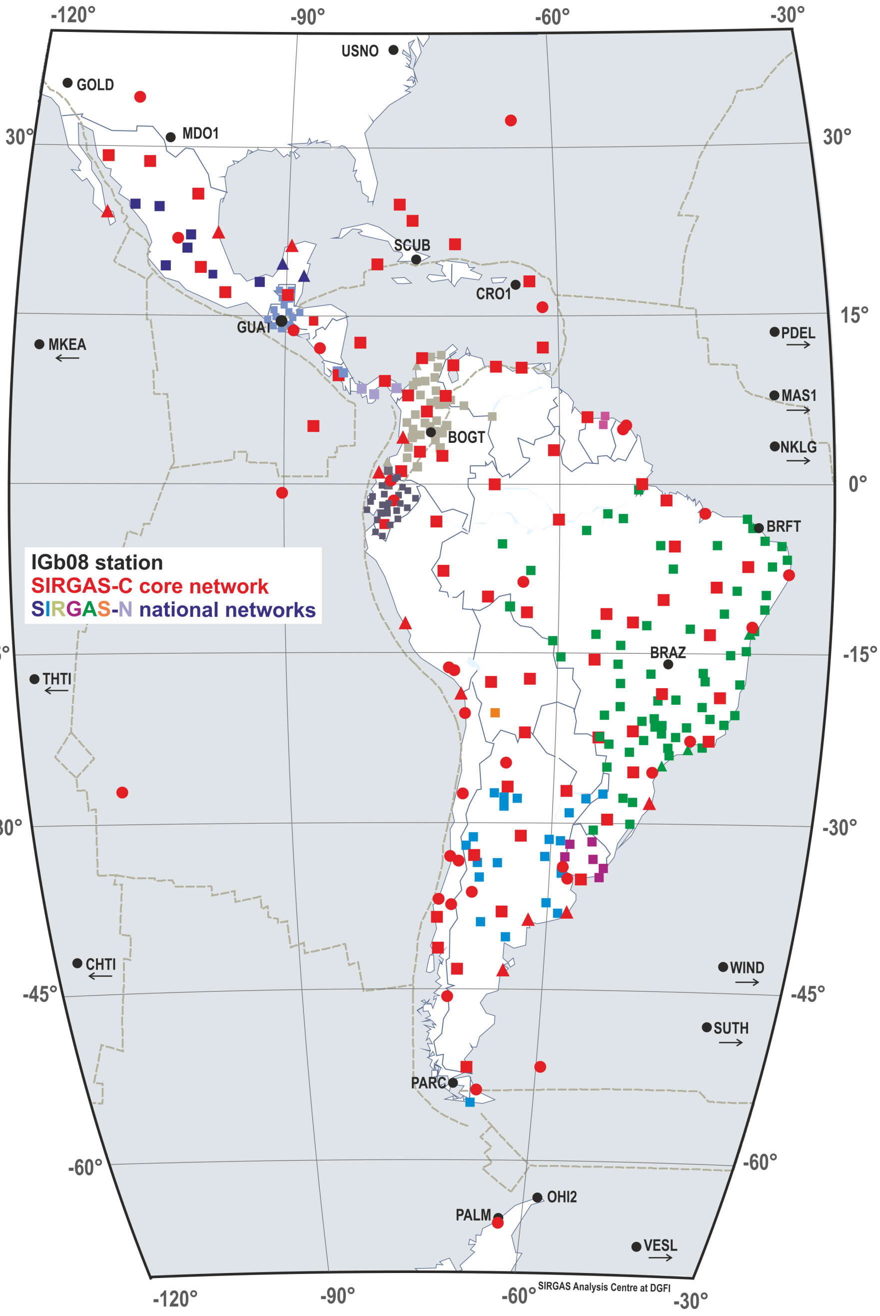

Figure 1: SIRGAS network (as of December 2013).

loosely constrained weekly solutions for the SIRGAS–N national networks, which are combined with the SIRGAS–C core network to get homogeneous precision for station positions and velocities. The individual solutions are combined by the SIRGAS Combination centers currently operated by DGFI (Germany) and IBGE (Brazil).

2 Routine processing of the SIRGAS reference frame

The SIRGAS processing centers follow unified standards for the computation of the loosely constrained solutions (e.g., Costa et al. (2012), Natali et al. (2009), Seemüller et al. (2012)). These standards are generally based on the conventions outlined by the IERS and the GNSS–specific guidelines defined by the IGS; with the exception that in the individual SIRGAS solutions the satellite orbits and clocks as well as the Earth orientation parameters (EOP) are fixed to the final weekly IGS values (SIRGAS does not compute these parameters), and positions for all stations are constrained to ±1 m (to generate the loosely constrained solutions in SINEX format). INEGI (Mexico) and IGN–Ar (Argentina) employ the software GAMIT/GLOBK (Herring et al. 2010); the other local processing centers use the *Bernese GPS Software* Ver. 5.0 (Dach et al. 2007). At the moment, the SIRGAS Local Processing centers align their procedures to the new standards described in the IERS Conventions 2010 (Petit and Luzum 2010) and to the characteristics specified by the IGS for the second reprocessing of the IGS global network (`http://acc.igs.org/reprocess2.html`). The IGS RNAAC SIR applies these new standards since July 2013 and is employing the *Bernese GNSS Software* Ver. 5.2 (Dach et al. (2007), (2013)). It is expected that the other processing centers start delivering solutions based on the new standards in January 2014.

3 Kinematics of the SIRGAS reference frame

To estimate the kinematics of the SIRGAS reference frame, a cumulative (multi–year) solution is computed (updated) every year, providing epoch positions and constant velocities for stations operating longer than two years. As the introduction of ITRF2008 (i.e. IGS08/IGb08) as the reference frame for the generation of the IGS products caused a discontinuity of some mm in the station position time series, the computation of multi–year solutions for the SIRGAS reference frame was discontinued until getting weekly normal equations referring to the ITRF2008 and covering a time span of at least three years. It is decided that SIRGAS will reprocess the entire SIRGAS network following IGS procedures and applying the new standards from January 1997 to present. However, while the SIRGAS Local Processing centers are unable to apply these, a new multi–year solution was computed for the SIRGAS–C core network only, i.e., for the stations processed routinely by the IGS RNAAC SIR. Main objective of this multi–year solution is to identify possible secular effects caused by the Maule earthquake of February 2010 in the kinematics of the

SIRGAS reference frame.

4 New processing standards for the SIRGAS reference frame

The standards applied for the generation of the weekly free normal equations for the new cumulative SIRGAS solution are:

- Basic observable: ionosphere–free linear combination;
- Sampling rate: 30 sec;
- Elevation cut–off angle: 3 deg;
- Elevation–dependent weighting of observations: $1/\cos^2 z$, with z being the zenith distance;
- Satellite orbits, satellite clock offsets, and EOP fixed to the combined IGS weekly solutions (Dow et al. (2009), http://www.igs.org/components/prods.html) referring to the IGS08/IGb08 frame. Since the IGS products refer to IGS08/IGb08 since April 2011 (GPS week 1632), the normal equations for previous weeks (backwards until April 2010) were computed using the satellite products and EOP generated by the IGS processing center CODE (center for Orbit Determination in Europe, ftp://ftp.unibe.ch/aiub/CODE/);
- Application of antenna phase center offsets and direction–dependent phase center variation values consistent with the IGS08/IGb08 frame for both transmitting and receiving antennas; i.e., spacecraft–specific z–offsets, block–specific x– and y–offsets, and phase center variations for receiver and satellite antennas from model igs08.atx (Schmid et al. (2007), http://igs.org/igscb/station/general/pcv_archive);
- Antenna radome calibrations applied if given in the model igs08.atx. Otherwise, the radome effect is neglected and the standard antenna model (radome NONE) is used;
- Phase ambiguities for L1 and L2 solved using the quasi–ionosphere free (QIF) strategy of the *Bernese GNSS Software* Ver. 5.2 (Dach et al. 2007). In this step, the ionosphere models of CODE (ftp://ftp.unibe.ch/aiub/CODE/) are provided as input to increase the number of solved ambiguities;
- The tropospheric zenith delay is modelled using the Vienna Mapping Function 1 (VMF1, Böhm et al. (2006)). The a priori values (∼ dry part) are derived from gridded coefficients based on the climate numerical models of ECMWF (European center for Medium–Range Weather Forecasts) and made available by J. Böhm, TU Vienna, at http://ggosatm.hg.tuwien.ac.at/DELAY/GRID/VMFG/. These a priori values are refined by computing partial derivatives of the troposphere zenith delay parameters (∼ wet part) with 2h intervals (using also VMF1) within the network adjustment. In addition, to model azimuthal asymmetries, horizontal gradient pa-

rameters are estimated according to the model of Chen and Herring (1997);

- Tidal corrections for solid Earth tide, permanent tide, and solid Earth pole tide are applied as described in Petit and Luzum (2010). The ocean tide loading is reduced with the FES2004 model (Letellier 2004) and the atmospheric tidal loading caused by the semidiurnal constituents S1 and S2 is reduced following the model of van Dam and Ray (2010). 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 tidal loading are provided by T. van Dam at `http://geophy.uni.lu/ggfc-atmosphere/tide-loading-calculator.html`
- Ocean or atmospheric tide geocenter coefficients are not applied since this correction is already contained in the final IGS (and CODE) products;
- Non–tidal loadings as atmospheric pressure, ocean bottom pressure, or surface hydrology are not reduced;
- Daily free normal equations are computed by applying the double difference strategy using the *Bernese GNSS Software* Ver. 5.2 (Dach et al. (2007), (2013)). The baselines are created taking into account the maximum number of common observations for the associated stations;
- The seven daily free normal equations corresponding to a GPS week are combined for computing a weekly free normal equation. Stations with large residuals in any daily normal equation (more than ±20 mm in the horizontal component or more than ±30 mm in the vertical component) are reduced from the corresponding daily equation and the weekly combination is recomputed.

5 Multi–year solution SIR13P01

The input data for this new cumulative solution are the weekly free normal equations covering the time span from April 2010 (GPS week 1580) to June 2013 (GPS week 1744). Given that most of the existing ITRF stations in South America are affected by the earthquake in Chile in February 2010 (see e.g. Sánchez et al. 2013), further stations located in Europe, Africa, Oceania and North America (Fig. 2) are included in the SIRGAS computations to increase the availability of fiducial points.

Before combining the weekly normal equations, a time series analysis is performed to identify outliers and discontinuities in the station positions. The thresholds for outliers are defined by ±15 mm for north and east and ±30 mm for height (about fourfold the mean RMS). If outliers appear sporadically (without pattern), the station is reduced from the respective free normal equation. If outliers reflect a discontinuity, a new position is set up for the station. Once outliers are reduced and discontinuities are identified, the weekly normal equations are combined to a multi–year solution setting up constant station

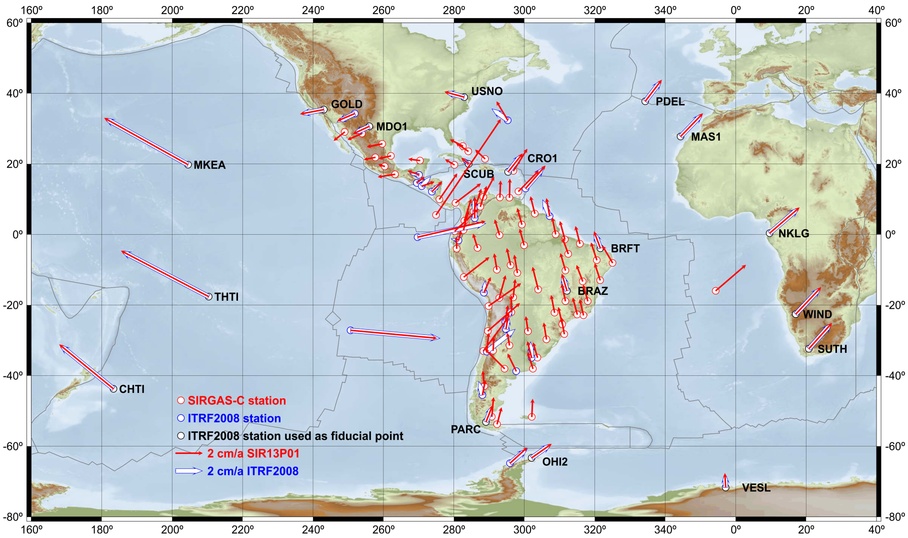

Figure 2: Horizontal velocities of the SIRGAS multi–year solution SIR13P01: it covers the time span from April 2010 to June 2013, includes 108 SIRGAS core stations and refers to ITRF2008, epoch 2012.0. (Stations with labels are fiducial points).

velocities (i.e. only linear station position variations are considered). The geodetic datum is realised by applying not–net–rotation and not–net–translation conditions with respect to the ITRF2008 coordinates (Altamimi et al. 2011) of selected IGb08 reference stations (Fig. 2). This procedure is carried out using the *Bernese GNSS Software* Ver. 5.2 (Dach et al. 2007)

The result of this computation is called solution SIR13P01 (Fig. 2). It includes positions and velocities for 108 SIRGAS core stations referring to the ITRF2008, epoch 2012.0. Its estimated precision is ±1.4 mm (horizontal) and ±2.5 mm (vertical) for the station positions at the reference epoch, and ±0.8 mm/yr (horizontal) and ±1.2 mm/yr (vertical) for the constant velocities. Stations showing very irregular post–seismic movements, like CONZ (Concepción, Chile) or ANTC (Antuco, Chile), are excluded because constant velocities (linear movements) are insufficient to model their behaviour (Fig. 3).

To evaluate the reliability of the SIR13P01 solution, different comparisons were performed (Tab. 1). The first comparison concentrates on the dissimilarities of the station positions and velocities at the fiducial points, i.e. the ITRF2008 values are compared with the values obtained in the SIR13P01 solution for the reference stations. The same procedure is repeated in a second comparison, but only taking into account those ITRF stations that were not used as fiducial points. Finally, the third comparison collates station position and velocities of the present solution with those values estimated in the last SIRGAS multi–year solution computed before the earthquake in February 2010 (i.e. the SIR10P01 solution, Seemüller et al. (2010)). The first and the second comparisons show the agreement between the new SIRGAS solution and ITRF2008; the third comparison should provide information

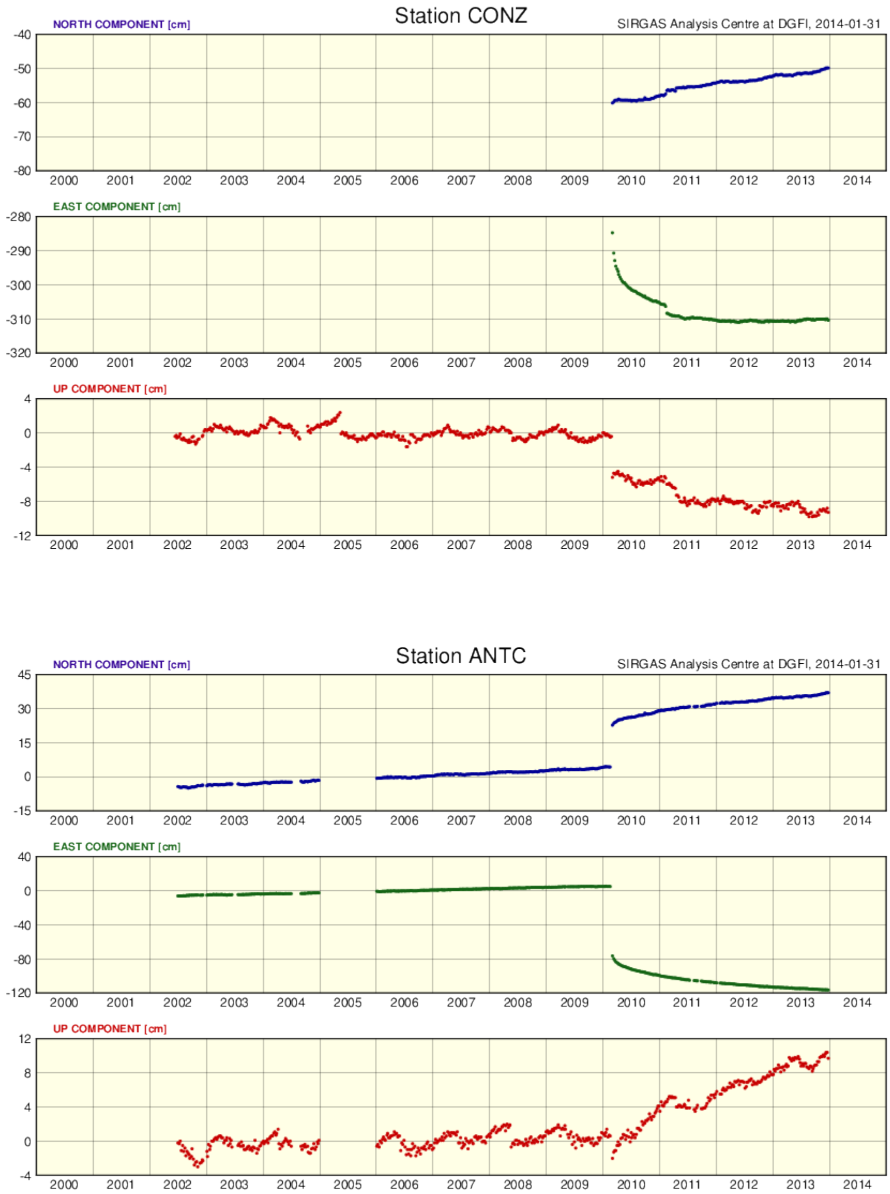

Figure 3: Time series of stations strongly affected by the Chilean earthquake in February 2010 (Concepción and Antuco).

Table 1: Comparison of the present SIR13P01 solution with ITRF2008 and the former solution SIR10P01 (computed before the Chilean earthquake in February 2010)

	Position [mm]			Velocity [mm/yr]		
	N	E	U	N	E	U
Comparison with ITRF2008, fiducial points only						
RMS	±3.2	±3.1	±3.8	±0.6	±1.1	±1.3
Mean	0.2	0.9	–0.9	–0.3	–0.1	0.6
Min	–6.5	–4.3	–7.8	–1.8	–2.0	–2.3
Max	4.6	8.3	7.0	1.8	1.9	2.4
Comparison with ITRF2008, non–fiducial points						
RMS	±8.2	±12.4	±13.7	±1.3	±3.2	±3.4
Mean	–0.1	9.8	–7.2	1.3	–0.3	–2.1
Min	–21.8	–25.8	–29.0	–3.1	–19.8	–8.9
Max	14.5	25.7	37.0	6.3	7.4	7.9
Comparison with SIR10P01						
RMS	±21.4	±39.5	±20.2	±1.3	±2.0	±2.7
Mean	–3.6	8.3	–5.9	1.0	–1.2	–1.3
Min	–88.3	–51.2	–26.2	–4.3	–19.8	–8.3
Max	130.5	588.3	130.59	6.8	3.7	11.5

about changes in the SIRGAS frame caused by the strong earthquake in Chile.

The discrepancies (for station positions and velocities) at fiducial points are within the coordinate accuracy of the ITRF2008 solution. Therefore, one could conclude that the new SIRGAS solution is appropriately aligned to this frame and it can be considered as its regional densification in Latin America and the Caribbean. The magnitudes obtained from the other two comparisons are on the contrary very large, in particular in the East component (Fig. 4). This means that older reference frame solutions (ITRF2008 or SIR10P01) differ significantly from the new realisation. Main reasons for this disagreement are:

- ITRF2008 and SIR10P01 do not reflect the effects (co–seismic and post–seismic movements) caused by the earthquake of February 2010 in the Southern part of

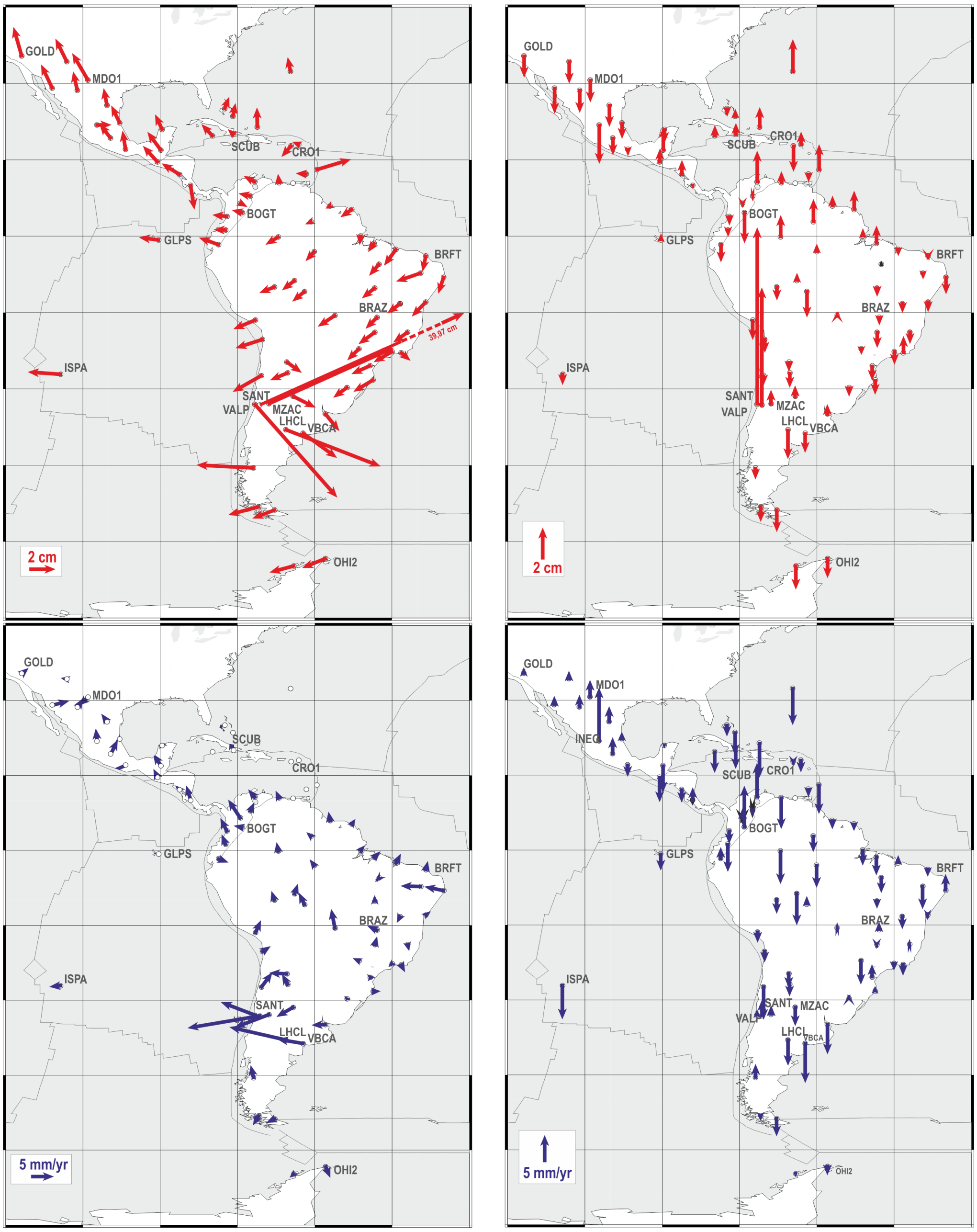

Figure 4: Horizontal (left) and vertical (right) residual position (upper two figures) and velocity (lower two figures) vectors between the SIR10P01 (before the earthquake in February 2010) and the SIR13P01 solutions.

South America;

- The weekly input solutions for ITRF2008 and SIR10P01 were computed with respect to the IGS05 frame, while SIR13P01 was computed with respect to the IGS08/IGb08 frame;
- Troposphere effects in SIR10P01 and SIR13P01 are modelled differently. Although the atmosphere parameters estimated within the network adjustment (∼ wet part) are very similar (some mm of discrepancy), the a priori zenith delay values (∼ dry part) differ by up to 5 cm, especially at those stations located in the tropical region;
- The datum realisation in SIR10P01 and SIR13P01 is based on different fiducial points. While the old solution includes reference stations located in Latin America only, the new solution also comprises reference stations located several thousand km away.

6 Outlook

Immediate plans concentrate on the reprocessing of the weekly SIRGAS normal equations backwards until January 1997 applying the new standards and considering the entire network. Therefore, the IGS RNAAC SIR takes care of the computations from 1997 until August 2008, when the first SIRGAS Local Processing centers started operating. From September 2008 until December 2013, the reprocessing includes the combination of the individual (reprocessed) solutions delivered by the SIRGAS Local Processing centers for the SIRGAS–N national networks.

7 Acknowledgements

The operational infrastructure and results described in this report are only possible thanks to the active participation of many Latin American and Caribbean colleagues, who not only make the measurements of the stations available, but also operate SIRGAS Analysis centers processing the observational data on a routine basis. This support and that provided by the International Association of Geodesy (IAG) and the Pan–American Institute for Geography and History (PAIGH) is highly appreciated. More details about the activities and new challenges of SIRGAS, as well as institutions and colleagues working on can be found at http://www.sirgas.org.

References

Altamimi, Z., X. Collilieux, and L. Métivier ITRF2008: an improved solution of the international terrestrial reference frame. *Journal of Geodesy*, 85(8):457–473, 2011. doi: 10.1007/s00190-011-0444-4.

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

Chen, G. and T.A. Herring. Effects of atmospheric azimuthal asymmetry on the analysis of space geodetic data *Journal of Geophysical Research*, 102(B9):20489–20502, 1997. doi: 10.1029/97JB01739.

Costa, S.M.A., A.L. Silva, and J.A. Vaz. Processing evaluation of SIRGAS–CON network by IBGE Analysis Center. In: *Geodesy for Planet Earth*, IAG Symposia, 136:859–868, 2012. doi: 10.1007/978-3-642-20338-1_108.

Dach, R., U. Hugentobler, P. Fridez., and M. Meindl (Eds.) Bernese GPS Software Version 5.0(Documentation) Astronomical Institute, University of Bern, 2007.

Dach, R. and the Bernese GNSS Software development team Bernese GPS Software: New features in version 5.2. Astronomical Institute, University of Bern, 2013. On–line available at http://www.bernese.unibe.ch/docs/BSW52_newFeatures.pdf.

Dow, J.M., R.E. Neilan, and C. Rizos. The International GNSS Service in a changing landscape of Global Navigation Satellite Systems *Journal of Geodesy*, 83:191–198, 2009. doi: 10.1007/s00190-008-0300-3.

Drewes, H., K. Kaniuth, C. Voelksen, S.M. Alves Costa, and L.P. Souto Fortes. Results of the SIRGAS campaign 2000 and coordinates variations with respect to the 1995 South American geocentric reference frame. In: *A Window on the Future of Geodesy*, IAG Symposia, 128:32–37, 1995. doi: 10.1007/3-540-27432-4_6.

Herring, T.A., R.W. King, and S.C. Mclusky. Introduction to GAMIT/GLOBK, Release 10.4. Massachusetts Institue of Technology, 2010. On–line available at http://www-gpsg.mit.edu/~simon/gtgk/Intro_GG.pdf.

Letellier, T. Etude des ondes de marée sur les plateux continentaux. Thèse doctorale, Université de Toulouse III, Ecole Doctorale des Sciences de l'Univers, de l'Environnement et de l'Espace, 2004.

Natali, M.P., M. Mueller, L. Fernández, and C. Brunini. CPLat: first operational experimental processing center for SIRGAS in Argentina. *Journal of Geodesy*, 83(3): 219–226, 2009. doi: 10.1007/s00190-008-0270-5.

Petit, G. and B. Luzum (Eds). IERS Conventions (2010). IERS Technical Note 36, Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, 2010. URL: http://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn36.html.

Sánchez, L. IGS Regional Network Associate Analysis center for SIRGAS(IGS RNAAC SIR). In: Meindl, M., R. Dach, Y. Jean (Eds): *IGS Technical Report 2011*, IGS Central Bureau, pp. 107–115, 2012.

Sánchez, L. IGS Regional Network Associate Analysis center for SIRGAS(IGS RNAAC SIR). In: R. Dach, Y. Jean (Eds): *IGS Technical Report 2012*, IGS Central Bureau, pp. 111–120, 2013.

Sánchez, L. and C. Brunini. Achievements and challenges of SIRGAS. In: *Geodetic Reference Frames*, IAG Symposia, 134:161–166, Springer Berlin Heidelberg, 2009. doi: 10.1007/978-3-642-00860-3_25.

Sánchez, L. W. Seemüller, and M. Seitz. Combination of the weekly solutions delivered by the SIRGAS processing centers for the SIRGAS–CON reference frame. In: *Geodesy for Planet Earth*, IAG Symposia, 136:845–851, 2012. doi: 10.1007/978-3-642-20338-1_106.

Sánchez, L. W. Seemüller, H. Drewes, L. Mateo, G. González, A. Silva , J. Pampillón, W. Martínez, V. Cioce, D. Cisneros, and S. Cimbaro. Long–term stability of the SIRGAS reference frame and episodic station movements caused by the seismic activity in the SIRGAS region. In: *Reference Frames for Applications in Geosciences*, IAG Symposia, 138:153–161, 2013. doi: 10.1007/978-3-642-32998-2_24.

Schmid, R., P. Steigenberger, G. Gendt, M. Ge, and M. Rothacher. Generation of a consistent absolute phase center correction model for GPS receiver and satellite antennas. *Journal of Geodesy*, 81(12):781–798, 2007. doi: 10.1007/s00190-007-0148-y.

Seemüller, W., L. Sánchez, M. Seitz, and H. Drewes. The position and velocity solution SIR10P01 of the IGS Regional Network Associate Analysis center for SIRGAS (IGS RNAAC SIR). *DGFI Report* No. 86., 2010.

Seemüller, W., M. Seitz, L. Sánchez, and H. Drewes. The new multi–year position and velocity solution SIR09P01 of the IGS Regional Network Associate Analysis center (IGS RNAAC SIR) *Geodesy for Planet Earth*, IAG Symposia, 136:877–883, 2012. doi: 10.1007/978-3-642-20338-1_110.

SIRGAS. SIRGAS Final Report; Working Groups I and II IBGE, Rio de Janeiro; 96 p. 1997. Available at http://www.sirgas.org.

van Dam, T. and R. Ray. S1 and S2 atmospheric tide loading effects for geodetic applications. 2010. Data set accessed 2013–06–01 at http://geophy.uni.lu/ggfc-atmosphere/tide-loading-calculator.html.