Long-Term Stability of the SIRGAS Reference Frame and Episodic Station Movements Caused by the Seismic Activity in the SIRGAS Region

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Abstract

The western part of the SIRGAS region is an extremely active seismic area because it is located in the plate boundary zone of six tectonic plates, namely the Pacific, Cocos, Nazca, North American, Caribbean, and South American plates. The frequent occurrence of earthquakes causes episodic station movements, which affect the long-term stability of the SIRGAS reference frame. Normally, these episodic events are taken into account in the frame realisation by introducing new position and, optionally, velocity parameters for the affected stations. However, this is not enough to guarantee the high precision required in a reference frame such as SIRGAS. Additional analyses about the post-seismic behaviour of the reference stations are necessary to allow the precise transformation between pre-seismic and post-seismic (deformed) frames. According to this, the paper presents an evaluation of the long-term stability of the SIRGAS reference frame including the comparison of the different SIRGAS realisations and the analysis of station displacements caused by earthquakes in the SIRGAS region. Special care is given to the events happened in

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Arequipa (on 2001-06-23, M = 8.4) and Chile (on 2010-02-27, M = 8.8). The analysis is based on the SIRGAS Continuously Operating Network (SIRGAS-CON). Beside analysing the station position time series and estimating the displacement vectors of the SIRGAS reference stations, some recommendations to mitigate the impact of this kind of events in the use of SIRGAS as a reference frame are formulated.

1   Introduction

Terrestrial reference frames supporting precise positioning based on global navigation satellite systems (GNSS) must be consistent with the reference frame in which the orbits of the GNSS satellites are determined. At present, the conventional reference frame is the ITRF (International Terrestrial Reference Frame), which is computed and maintained by the International Earth Rotation and Reference Systems Service (IERS). According to the IERS conventions (Petit and Luzum 2010), the International GNSS Service (IGS) determines and provides the GNSS satellite ephemeris referring to the ITRF (Dow et al. 2009). Users applying IGS orbits for processing GNSS positioning have also to introduce terrestrial reference stations referring to the ITRF. The accessibility to this frame at regional and local levels is guaranteed through (1) regional (continental) densifications of the global frame, and (2) national densifications of the continental frames. Following this hierarchy, SIRGAS (Sistema de Referencia Geocéntrico para las Américas) is realised by a regional densification of the ITRF in Latin America and the Caribbean (Brunini et al. 2012), and it is further extended to each country by the national reference networks.

2   SIRGAS Realisations

Initially, SIRGAS was realised by means of two continental GPS campaigns:

1. SIRGAS95 including 58 stations distributed over South America observed for 10 days in May 1995 and resulting in station positions referred to the ITRF94, epoch 1995,4 (SIRGAS 1997).
2. SIRGAS2000 with 184 stations including the SIRGAS95 points and additional stations located in the Caribbean, Central, and North America. It was measured during 10 days in May 2000 and its station positions refer to ITRF2000, epoch 2000,4 (Drewes et al. 2005).

Today, SIRGAS is realised by a network of about 230 continuously operating GNSS stations. This so-called SIRGAS-CON network (Fig. 24.1) replaces the first two SIRGAS realisations and allows a permanent monitoring of the frame.

SIRGAS-CON is weekly processed by the SIRGAS Analysis Centres; main products of this processing are (Brunini et al. 2012): loosely constrained weekly solutions for station positions to be included in the IGS global polyhedron and in multi-year solutions of the network; and weekly station positions aligned to the ITRF for further applications in Latin America. The weekly free normal equations are solved using a set (see Fig. 24.2) of the same ITRF reference stations selected by the IGS to compute the GNSS orbits, i.e. the IGS reference frame (Kouba 2009), at present, the IGS05 (http://www.igs.org/network/refframe.html). The datum realisation is given by constraining the weekly positions of the IGS reference stations determined within the IGS weekly combination (solutions igsyyPwwww.snx, Dow et al. 2009).

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 2 years. 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 SIR10P01 refers to ITRF2008, epoch 2005.0 (Seemüller et al. 2010). SIR10P01 includes all the weekly normal equations provided by the SIRGAS analysis centres from January 2, 2000 (GPS week 1,043) to June 5, 2010 (GPS week 1,586) and provides positions and velocities for 183 reference stations (Fig. 24.2). Its precision was estimated to be ~±0.5 mm (horizontal) and ~±0.9 mm (vertical) for the station positions at the reference epoch, and ~±0.2 mm/a (horizontal) and ~±0.4 mm/a (vertical) for the constant velocities, respectively. Precision is understand here as the solution repeatability within the SIRGAS-CON network processing. The comparison of the SIRGAS coordinates with the ITRF2008 coordinates for common points delivers the accuracy of the solution; i.e. the measure of the solution uncertainty with respect to the ITRF2008. This was assessed to be N = 0.8 ± 5.0 mm, E = 0.3 ± 3.6 mm and Up = −4.9 ± 8.6 mm
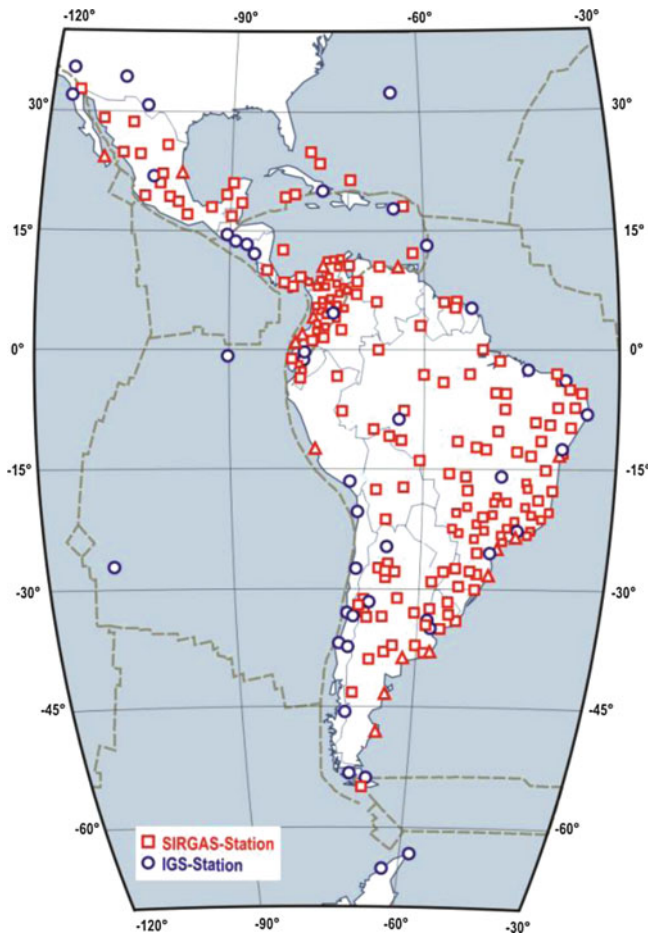
Fig. 24.1 SIRGAS reference frame (status October 2010)

Fig. 24.2 Horizontal velocities of the SIR10P01 multi-year solution. Velocities of ITRF2008 stations are included for comparison

for station positions and $V_N = -0.1 \pm 1.1$ mm/a, $V_E = -0.1 \pm 1.1$ mm/a and $V_{Up} = 0.0 \pm 2.2$ mm/a for station velocities.

On this basis, most of the Latin-American countries adopted SIRGAS as the official national reference frame with station positions associated to a certain (conventional) epoch and to be extrapolated to any other epoch using the velocities, or – if not available for new stations – by applying the SIRGAS weekly solutions.

As reference frame, SIRGAS is the backbone for implementing applications associated to geo-referenced data such as land management, geo-spatial data infrastructures, property lines, country boundaries, etc. These applications need coordinates compatible in time and with long-term stability, i.e. all station positions referring to the measurement epoch and to the current ITRF shall be precisely transformed to the conventional epoch and to the ITRF adopted within the national reference frame. According to this, this study (1) evaluates the sustainability of the different SIRGAS realisations (SIRGAS95, SIRGAS2000 and multi-year solutions of SIRGAS-CON); (2) presents the episodic station movements caused by the
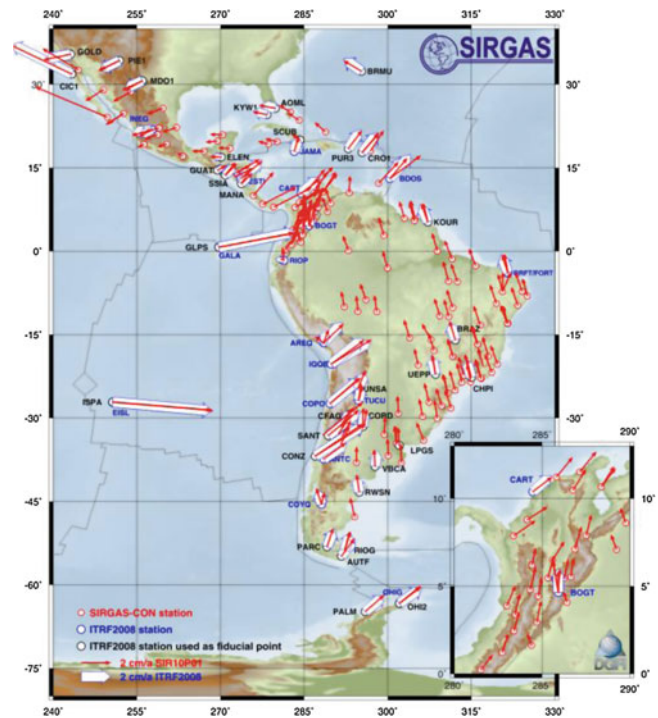
seismic activity in the SIRGAS region since 2000; and (3) formulates a strategy to reduce the lack of precision due to the transformation between the pre-seismic and post-seismic (deformed) frame realisation.

3 Sustainability of the SIRGAS Reference Frame

The former SIRGAS realisations (SIRGAS95 and SIRGAS2000) as well as the multi-year solutions of the SIRGAS-CON network include those models, standards, and strategies widely applied at the time in which they were computed; e.g. different ITRF solutions, ocean tide loading, a priori ionosphere models for ambiguity resolution, relative corrections for the phase centre variations until 2006 and absolute corrections afterwards, etc.; see for SIRGAS95 (SIRGAS 1997), for SIRGAS2000 (Drewes et al. 2005), and for SIRGAS-CON (e.g. Seemüller et al. 2008, 2010a, Seemüller 2009).

Figure 24.3 summarizes the main characteristics of the different SIRGAS multi-year solutions. It should be noted that solutions computed since 2007 include the reprocessed normal equations for the weeks before November 2006 (GPS week 1,399). This reprocessing takes into account the IGS05 as reference frame and the antenna absolute phase centre corrections provided by the IGS (model igs05_1525.atx, see: http://igscb.jpl.nasa.gov/igscb/station/general/pcv_archive/).
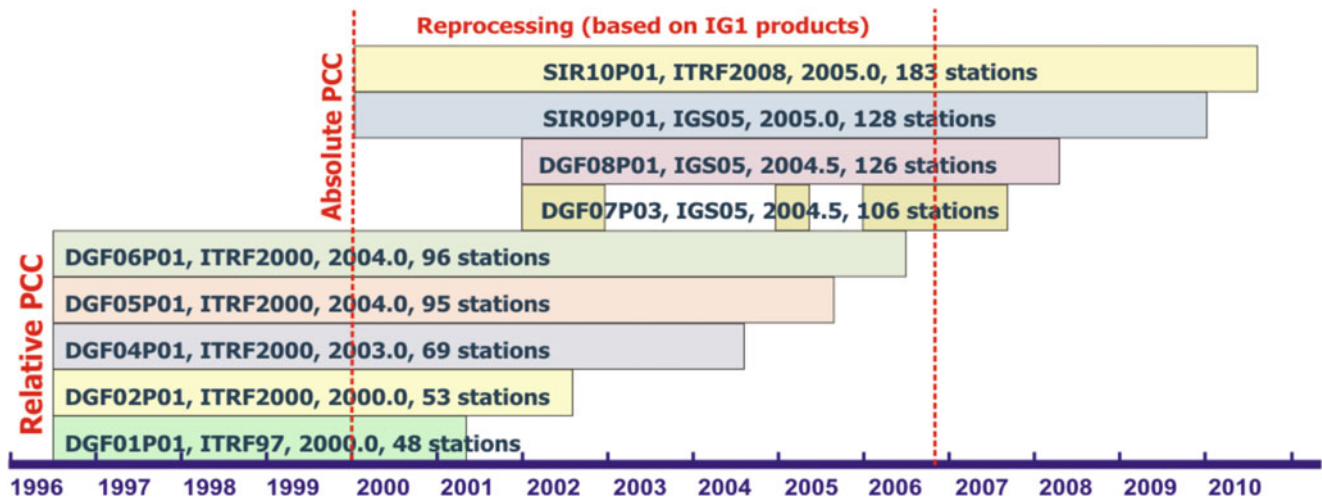
Fig. 24.3 Time spans, number of stations, and reference frame considered in the different SIRGAS multi-year solutions

Table 24.1 Comparison of the SIRGAS multi-year solutions with the ITRF2008

Solution	Common stations with ITRF2008	Comparison with the ITRF2008					
		Position deviations: Offsets ± RMS			Velocity deviations: Offsets ± RMS		
		N[mm]	E[mm]	h[mm]	VN[mm/a]	VE[mm/a]	Vh[mm/a]
DGF01P01	27	-16,3 ± 8,0	7,2 ± 19,5	27,9 ± 16,2	-0,4 ± 2,6	3,1 ± 4,7	1,3 ± 4,5
DGF02P01	24	-2,4 ± 3,7	-2,5 ± 5,8	4,0 ± 13,9	1,1 ± 1,6	1,4 ± 2,1	-3,7 ± 6,7
DGF04P01	35	-0,4 ± 4,3	-3,4 ± 5,0	1,3 ± 14,9	1,9 ± 2,3	1,3 ± 2,1	0,1 ± 3,6
DGF05P01	34	0,2 ± 3,8	-2,0 ± 5,0	0,1 ± 13,1	1,8 ± 2,1	1,1 ± 2,1	1,2 ± 3,6
DGF06P01	32	0,0 ± 3,9	-1,7 ± 4,9	1,1 ± 12,3	2,0 ± 2,2	1,0 ± 1,9	0,8 ± 3,0
DGF07P03	22	-1,3 ± 5,1	0,9 ± 6,2	-4,4 ± 19,5	0,5 ± 1,3	-0,4 ± 1,3	0,5 ± 2,7
DGF08P01	28	-3,2 ± 5,1	1,1 ± 8,9	-8,0 ± 10,0	0,5 ± 1,3	-0,5 ± 1,6	1,0 ± 2,3
SIR09P01	34	0,3 ± 4,0	-0,6 ± 6,7	-5,1 ± 12,0	0,3 ± 1,0	0,0 ± 1,1	-0,2 ± 1,9
SIR10P01	74	0,8 ± 5,0	0,3 ± 3,6	-4,9 ± 8,6	-0,1 ± 1,1	-0,1 ± 1,1	0,0 ± 2,2

To evaluate the sustainability of the SIRGAS realisations, following steps were considered:

1. The different SIRGAS multi-year solutions are compared with the ITRF2008. For this purpose, the SIRGAS-CON multi-year solutions are transformed to ITRF2008 and the coordinate comparison is done for epoch 2000,0.
2. The SIRGAS95 and SIRGAS2000 realisations are compared with the latest SIRGAS-CON multi-year solution (SIR10P01). This comparison is done in the ITRF2008 reference frame and at the conventional epochs of the former realisations, i.e. 1995,4 and 2000,4.

In both cases, the transformation parameters presented in the IERS Conventions (Table 4.1, Petit and Luzum 2010) are applied and stations affected by earthquakes are excluded (see Sect. 4).

Table 24.2 Comparison of SIRGAS95 and SIRGAS2000 with the multi-year solution SIR10P01

Realization	Common stations	Comparison with SIR10P01		
		Position deviations: Offsets ± RMS		
		N[mm]	E[mm]	h[mm]
SIRGAS95	19	-21,3 ± 4,9	-18,7 ± 4,2	5,8 ± 18,3
SIRGAS2000	53	-0,3 ± 8,6	0,1 ± 7,5	-6,2 ± 10,3

Results (Tables 24.1 and 24.2) show a very good consistency between the different SIRGAS realisations. The largest discrepancies (~2 cm) were detected for the SIRGAS realisations referring to ITRF94 and ITRF97. Realisations referring to ITRF2000 and IGS05 have an agreement better

Table 24.3 Seismic events with high impact in the SIRGAS frame since 2000

Location	Date	M	Coordinate change	Affected stations
Mexicali, Mexico	2010-04-04	7,2	23 cm	MEXI
Chile	2010-02-27	8,8	1 to 305 cm	See table 5
Costa Rica	2008-01-08	6,1	2 cm	ETCG
Martinique	2007-11-29	7,4	1 cm	BDOS, GTK0
Copiapo, Chile	2006-04-30	5,3	2 cm	COPO
Tarapaca, Chile	2005-06-13	7,9	6 cm	IQQE
Managua, Nicaragua	2004-10-09	6,9	1 cm	MANA
Arequipa, Peru	2001-06-23	8,4	52 cm	AREQ
El Salvador	2001-02-13	7,8	4 cm	SSIA

than ±5 mm. This reflects the expected improvement of the frame as consequence of longer time series of station positions and the better new models, standards, and analysis strategies applied today.

4 Impact of Seismic Events on the SIRGAS Reference Frame

The western part of the SIRGAS region is located in the plate boundary zone between the Pacific, Cocos, and Nazca plates in the west and the North American, Caribbean, and South American plates in the east. The interaction of these drifting plates causes an extremely high seismic activity in this area, generating episodic station movements (Table 24.3) and deformations in the SIRGAS reference frame. The precise determination and modelling of co-seismic and post-seismic displacements is necessary to guarantee:

1. The reliability of the SIRGAS weekly positions estimated for the week when a seismic event occurs;
2. The appropriate transformation of station positions between the pre-seismic and the post-seismic (deformed) reference frame;
3. The long-term stability of the SIRGAS reference frame.

According to this, always when a strong earthquake shakes the SIRGAS region, the SIRGAS Analysis Centres attempt to process as soon as possible the available GNSS measurements to estimate the impact on the reference frame. The usual procedure is based on the computation of free daily normal equations, which include IGS reference stations located outside the SIRGAS region, i.e. in Europe, North America, Africa, and Antarctica. These external IGS stations are used for the datum definition in the solution of the normal equations and as fiducial points for the calculation of a similarity transformation between the pre-seismic and post-

seismic networks. By comparing daily station positions and the geometry of the network before and after the earthquake, it is possible to determine displacements of the SIRGAS reference stations associated to the seism. In the same way, the analysis of station position time series allows to estimate further post-seismic movements and/or significant changes in the constant velocity of the affected stations. As examples, the displacements generated by the earthquakes of Arequipa, Peru (on 2001-06-23), and Chile (on 2010-02-27) are described in the following.

The basic procedure for the determination of daily station positions before and after any earthquake is:

- Elevation mask and data sampling rate are set to 3 ° and 30 s, respectively.
- Absolute calibration values for the antenna phase centre corrections published by the IGS are applied.
- Satellite orbits, satellite clock offsets, and Earth orientation parameters are fixed to the combined IGS weekly solutions (Dow et al. 2009).
- Phase ambiguities for L1 and L2 are solved by applying the quasi ionosphere free (QIF) strategy of the Bernese software (Dach et al. 2007).
- Periodic site movements due to ocean tide loading are modelled according to the FES2004 ocean tide model (Letellier 2004). The corresponding values are provided by M.S. Bos and H.-G. Scherneck at http://129.16.208.24/loading/.
- Zenith delays due to tropospheric refraction (∼wet part) are estimated at a 2 h interval within the network adjustment and mapped to zenith using the Niell (1996) wet mapping function. The a priori zenith delays (∼dry part) are modelled using the Saastamoinen (1973) model and mapped to zenith using the Niell (1996) dry mapping function.
- Daily free normal equations are computed by applying the double difference strategy (Bernese Software 5.0, Dach et al. 2007). The baselines are created taking into account the maximum number of common observations for the associated stations. Afterwards, loosely constrained daily solutions for station positions are generated by constraining all station coordinates to ±1 m. These loosely constrained solutions are used to compare the network geometry before and after the earthquake.
- The daily normal equations are separately solved with respect to selected IGS reference stations located outside the SIRGAS region. The geodetic datum is defined by constraining the coordinates of the reference stations to the positions calculated within the IGS weekly combinations (igsyyPwwww.snx or ig1yyPwwww.snx for reprocessed products). The applied constraints guarantee that the coordinates of the reference stations do not
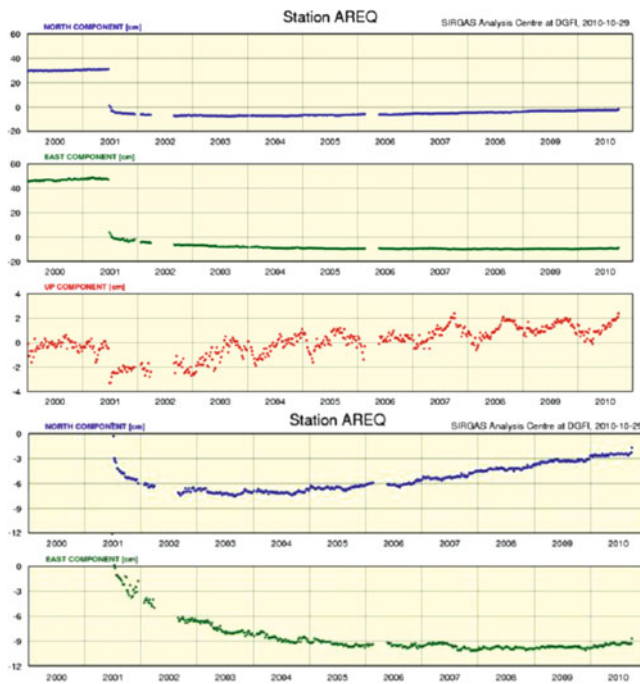
Fig. 24.4 Time series of station positions for AREQ. Lower pictures show a zoom of post-seismic displacements in the north and east components

Table 24.4 Station velocities estimated for AREQ before and after the earthquakes occurred in June and July 2001

Time span		Velocities [m/a]	
from	to	North	East
1996-06-03	2001-06-24	0,0118	0,0126
2001-06-25	2001-08-07	-0,4919	-0,4611
2001-08-08	2001-09-11	-0,0390	-0,1174
2001-09-12	2002-08-25	-0,0202	-0,0400
2002-08-26	2007-12-03	0,0042	-0,0056
2007-12-04	2010-06-06	0,0089	0,0033

Table 24.5 Residuals after a similarity transformation between the station positions computed for the GPS weeks 1572 (2010-02-24) and 1573 (2010-03-03). For station ANTC positions of week 1539 (2009-07-08) were used

	Residuals		
Station	N (mm)	E (mm)	Up (mm)
ANTC	195	−808	−12
AZUL	1	−23	3
BCAR	3	−16	3
CFAG	−18	−33	1
CONZ	−682	−2977	−47
CSLO	−21	−36	6
IGM1	−5	−18	8
LHCL	16	−66	4
LPGS	−2	−17	−1
MA01	37	−83	9
MZAC	−48	−109	15
MZAE	−39	−105	17
MZAS	−27	−210	18
RWSN	8	−10	3
SANT	−145	−257	−21
SL01	−21	−64	1
SRLP	3	−58	8
UCOR	−11	−22	1
UNRO	−7	−19	−3
UNSJ	−18	−29	−1
UYMO	−1	−11	10
VALP	−13	−76	−137
VBCA	8	−30	4

change more than 1.5 mm within the SIRGAS adjustment (Sánchez et al. 2012). In this study, the IGS05 reference frame is applied.

– Finally, residual position time series are generated. For this, the daily solutions are transformed to a pre-seismic reference frame (e.g. the SIRGAS weekly solution for the previous week to the earthquake or the latest available SIRGAS-CON multi-year solution) by a seven-parameter similarity transformation. The residual time series are analysed to detect discontinuities or changes in the movement trend of the SIRGAS sites.

Applying this strategy we analysed the GPS measurements registered by the station AREQ (Arequipa, Peru) before and after the two earthquakes (with magnitudes 8.4 and 7.6) on 2001-06-23 and 2001-07-07. It was possible to determine co-seismic displacements of 52.3 cm and 3.5 cm in SW-direction. The station position time series (Fig. 24.4) shows that the station moved horizontally for more than 2 years in the opposite direction as was usual before the earthquake. During the weeks following the earthquakes, velocities of 1.8 mm/day and 1.0 mm/day, respectively, were estimated (Kaniuth et al. 2002). Afterwards, the station presents a creeping movement with a slowing down post-seismic velocity until December 2007, when its trend has again the same direction and a similar velocity as in the pre-seismic period (Table 24.4).

The biggest impact produced by an earthquake on the SIRGAS reference frame corresponds to the seism (M = 8.8) that occurred on 2010-02-27 in Chile. 23 SIRGAS reference stations moved more than 1.5 cm (Table 24.5). The largest displacements were detected between latitudes 30°S and 40°S from the Pacific to the Atlantic coast (Fig. 24.5). Results show that the station CONZ (Concepción, Chile) initially moved 305.4 cm in the SW-direction. In the 2 weeks following the first earthquake, additional post-seismic movements of about 10 cm were identified. Until now (October 2010), this station moved 9 cm more in the E-direction (Fig. 24.6)
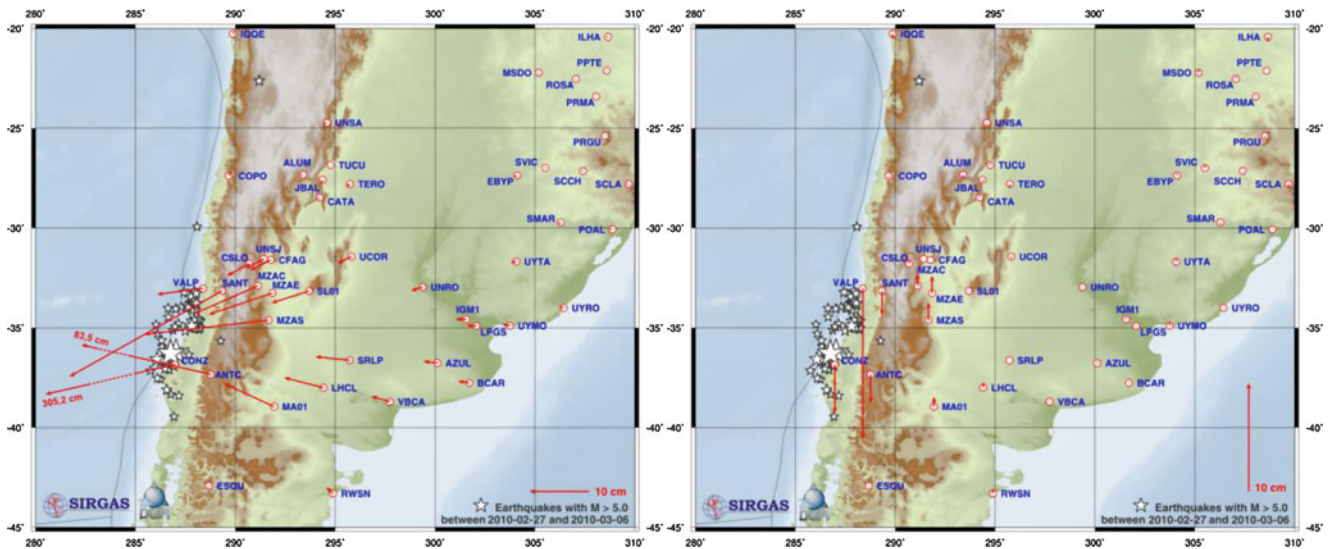
Fig. 24.5 Station displacements caused by the earthquake occurred on 2010-02-27 in Chile
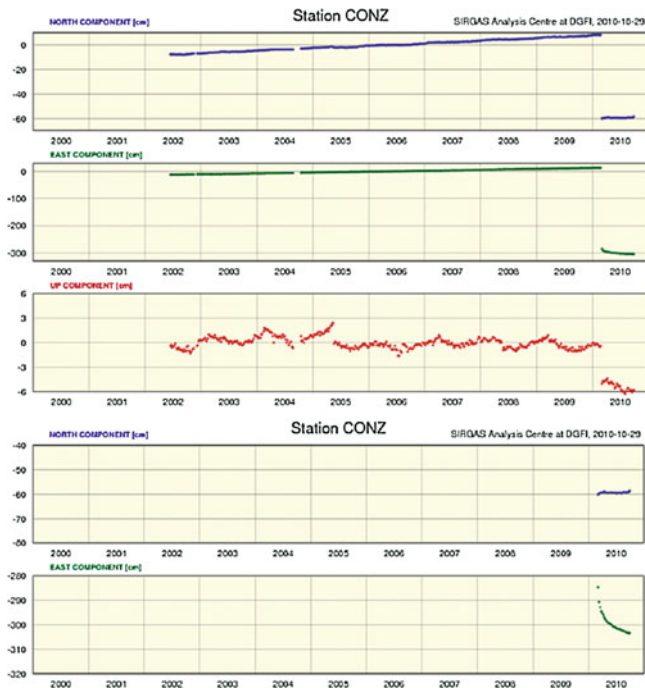

Fig. 24.6 Time series of station positions for CONZ. Lower pictures show a zoom of post-seismic displacements in the north and east components

Table 24.6 Station velocities estimated for CONZ after the earthquake occurred on 2010-02-27

Time span		Velocities [m/a]	
from	to	North	East
2010-03-21	2010-05-08	-0,0111	-0,4043
2010-05-09	2010-07-17	-0,0071	-0,1488
2010-07-18	2010-10-02	0,0315	-0,0856

Strong vertical co-seismic displacements were also identified in Concepción (CONZ), Santiago (SANT), Valparaíso (VALP) and the Province of Mendoza (MZAC, MZAE, MZAS) in Argentina. Stations located in the west of the Andes moved downwards, stations located in the east moved upwards (Fig. 24.5). Time series of station positions for CONZ (Fig. 24.6) and other close stations (ANTC, SANT, VALP, MZAS) shows that the post-seismic displacement in the east component presents the same behaviour observed in station AREQ. Table 24.6 summarizes the linear trends of the post-seismic time series for the north and east components. At present, we are not yet able to determine the effect of this earthquake on the reference frame because it is necessary to analyse cumulative solutions of more than 2 years after its occurrence.

5   Modelling Seismic Effects Within Reference Frames

To guarantee the long-term stability of the reference frame, it is necessary to enable the transformation between the pre-seismic and the post-seismic frame realisations. This transformation cannot be done by usual approaches (like affine or seven-parameter similarity transformations) because the deformed network does not fulfil the similarity condition; i.e. changes occurred in the geometry of the network due to the earthquake cannot be sufficiently represented by means of rotations, translations or scale factor.

Effects of seismic events are normally taken into account by introducing new position and/or velocity parameters for the affected stations. Nevertheless, earthquakes of big magnitudes generate not only jumps in the position of the

reference stations, but also change their "normal" movement (constant velocities) mainly caused by plate tectonics. The analysis of the coordinate time series of station AREQ (Arequipa, Peru) shows that this "normal" tectonic movement is recovered after a long period (almost 10 years in this case, Fig. 24.4). When a reference station shows a non-linear behaviour after the earthquake, the post-seismic period is cut into short time intervals ΔT_i to model the movement by a sequence of constant velocities V_i (one velocity per each interval), e.g. see AREQ in the ITRF2008 solution (http://itrf.ensg.ign.fr/ITRF_solutions/2008/ITRF2008.php). To transform the station positions before and after the seismic event, one has to sum up all the intervals ($\Delta X = \Sigma V_i * \Delta T_i$). This approximation is insufficient for SIRGAS because:

– The national reference frames contain a high percentage of non-continuously operating stations and the sequence of velocities after an earthquake cannot be reliably determined.
– The selection of the time intervals to compute constant velocities approximating the non-linear movement of a station is open to more than one interpretation; i.e. it cannot always be unambiguous and estimated velocities can significantly vary from one computation to other one.
– The determination of velocities for too short time intervals (less than 2 years) within the multi-year solutions of the SIRGAS reference frame is not reliable. This is because the seasonal (e.g. loading) signals contained in the station position time series are not considered up to now and they can mislead the velocity estimation (Brunini et al. 2012).
– The SIRGAS reference frame is composed of about 230 continuously operating stations; however, their geographical distribution does not provide the required density (coverage) to interpolate (model) the effects of the seismic events with high accuracy.

According to this, to mitigate the impact of this kind of events in the use of SIRGAS as reference frame in the different countries of the region, it is necessary:

– To continue improving the national reference frames by installing more continuously operating GNSS stations in order to precisely monitor possible deformations.
– After a strong seism like in Chile 2010, the reference networks composed by non-continuously operating stations must be re-measured as soon as possible.
– The transformation between the pre-seismic and the post-seismic frame realisations must be based on a deformation model derived from discrete (weekly) station positions. Usual network transformations (similarity or affine) cannot be applied.
– In stations not observed continuously, the post-seismic coordinate changes can be interpolated from the deformation model.

– In GNSS positioning of high precision, users of reference frames have to apply the epoch (weekly or monthly) positions instead of those derived from the reference epoch and (a sequence of) constant velocities.

6 Closing Remarks

Although the reliability of the estimated positions and velocities of the SIRGAS reference stations as well as its compatibility through time are demonstrated, it is necessary to give special care to the reference frame deformations caused by seismic events. This implies the permanent monitoring of the (continental and national) reference networks by means of continuously operating GNSS stations and the consequent modelling of the deformations caused by this type of events. Today, it is not possible to estimate a continuous deformation model representing the impact of the seism in Chile, because the SIRGAS reference stations are too sparse and the computations are not reliable. At present, Chile and Argentina are measuring again their national networks based on non-continuously operating stations. With these data and complementary GPS observations registered under different geophysical projects, the point densification shall be improved and then it will be possible to model the deformation with sufficient spatial resolution.

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