Modelling seismic effects in regional geodetic reference frames

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Motivation

The western part of South America, i.e. 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, is an extremely active seismic area. The frequent occurrence of earthquakes causes episodic station movements, which influence the long-term stability of the geodetic reference frames, i.e. the global ITRF (*International Terrestrial Reference Frame*) and its regional densification SIRGAS (*Geocentric Reference System for the Americas*). For instance, the earthquake in Chile on 2010-02-27 moved 23 reference stations between 1 cm and 3 m to the west (Fig. 1).

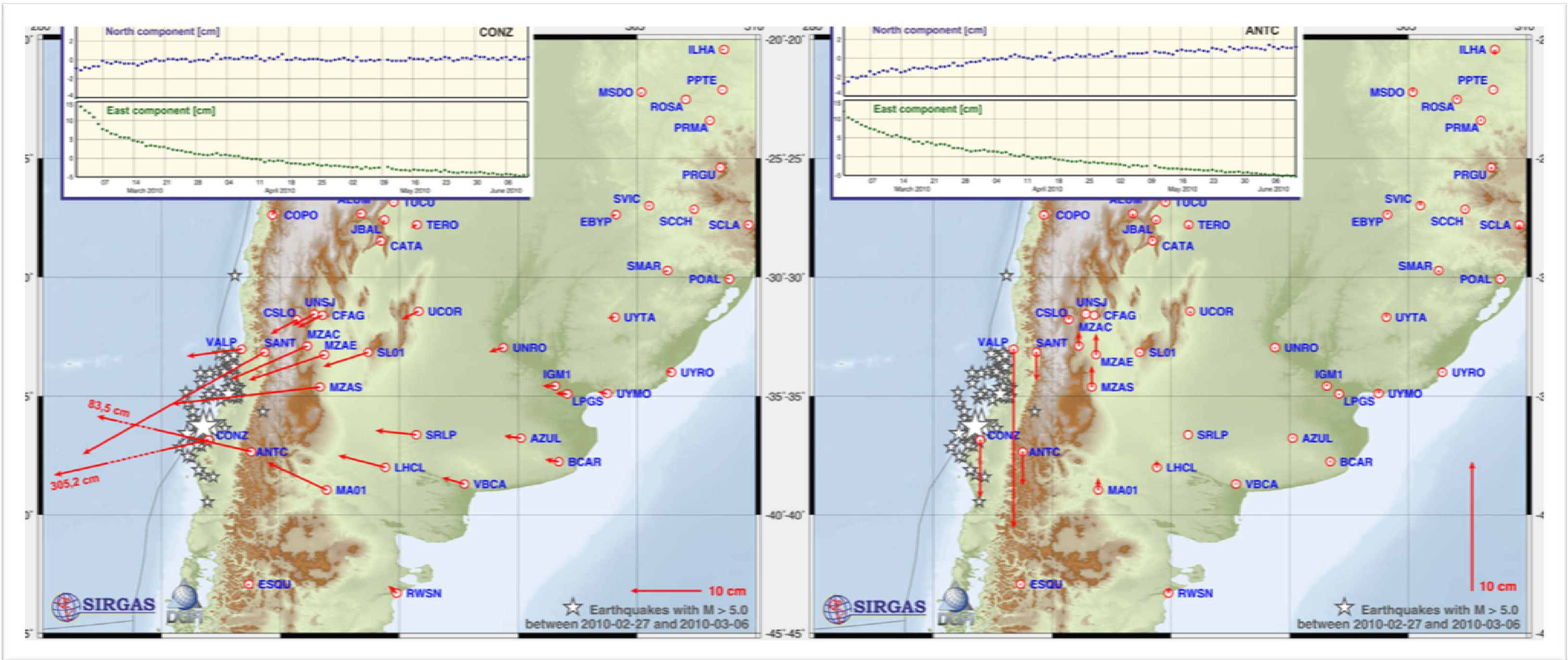

Fig. 1. Displacements caused by the earthquake in Chile on 2010-02-27. Time series show post-seismic movements in stations CONZ (Concepción) and ANTC (Antuco).

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The network deformation due to these events has to be determined to allow the precise transformation between the pre-seismic and the post-seismic coordinates. This cannot be done by usual approaches (like Helmert transformation) because the deformed networks do not fulfil the similarity condition. Earthquakes of big magnitudes generate not only jumps in the position of the reference stations, but also change their "normal" movement (constant velocities). When a reference station shows a non-linear behaviour after the earthquake (e.g. AREQ after 2001-06-23, Fig. 2), the post-seismic period is habitually cut into short time intervals ΔT_i to model the movement by a sequence of constant velocities V_i (Fig. 2). 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 because (1) the modelling (interpolation) of the seismic effects highly depends on the geographical distribution (coverage) of the continuously operating reference stations, and (2) the sequence of velocities after an earthquake cannot be reliably determined for non-continuously operating reference stations.

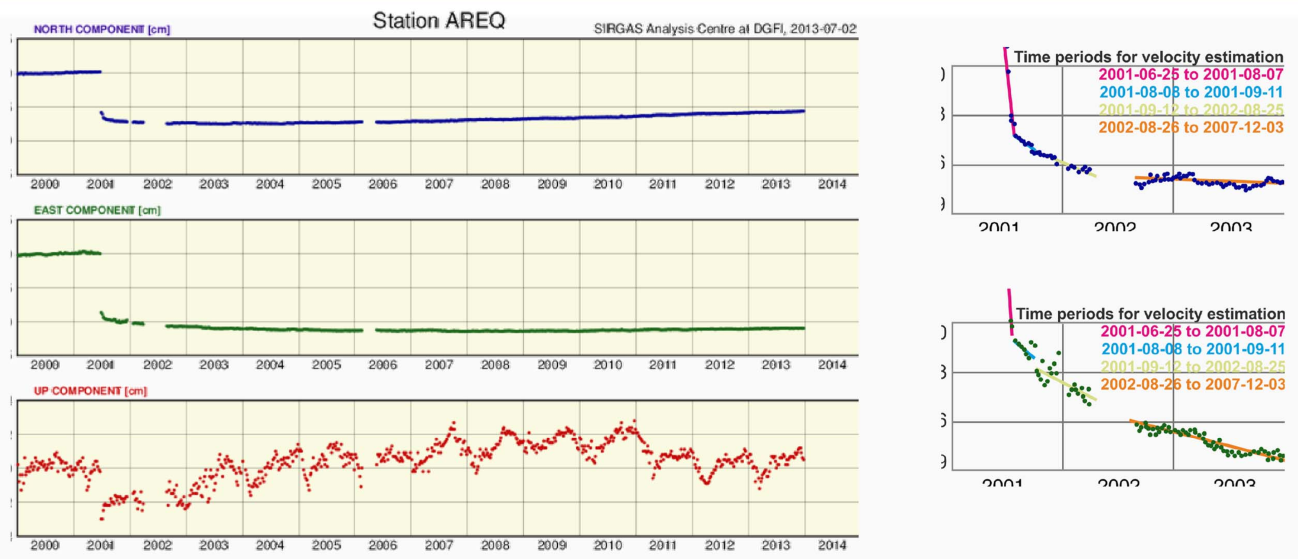

Fig. 2. Time series of station AREQ. Velocities for post-seismic displacements are displayed.

Post-seismic kinematics of the SIRGAS Reference Frame

A new cumulative solution for the SIRGAS Reference Frame was computed covering a time span of four years starting two months after the strong earthquake in Chile in February 2010. Given that most of the ITRF stations in South America were affected by this earthquake, further stations located in Europe, Africa, Oceania and North America (Fig. 3) are now considered for the SIRGAS computations to increase the availability of fiducial points. This solution includes reprocessed weekly normal equations based on the newest standards released by the IERS (*International Earth Rotation and Reference Systems' Service*) and the IGS (*International GNSS Service*). The geodetic datum is realised by applying not-net-rotation and not-net-translation conditions with respect to the IGb08 coordinates of the selected reference stations (Fig. 3). This procedure was carried out using the Bernese GNSS Software V.5.2 (Dach et al. 2007, 2013). The solution includes positions and velocities for 108 SIRGAS core stations referring to IGb08, 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.

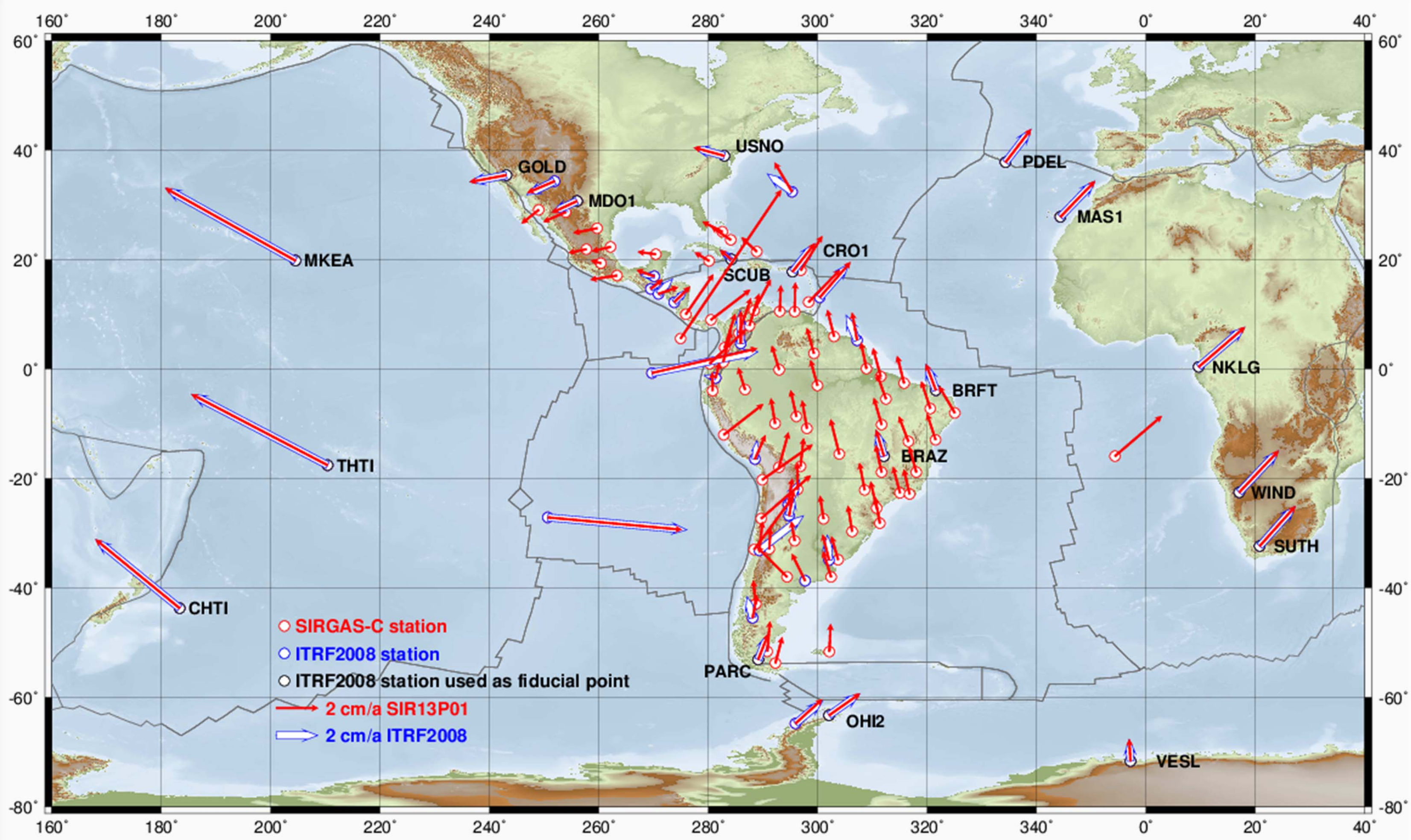

Fig. 3. Horizontal velocities of the post-seismic SIRGAS cumulative solution (stations with labels are fiducial points).

Recommendations

To mitigate the impact of seismic events in the use of SIRGAS, it is necessary:

- To improve the regional reference frame by installing more continuously operating GNSS stations to precisely monitor possible deformations;
- Reference networks composed by non-continuously operating stations must be replaced as far as possible by continuously operating stations. If this is not possible, they have to be re-measured immediately after a seism;
- The transformation between the pre-seismic and the post-seismic frame realizations must be based on a deformation model derived from discrete (weekly) station positions. The Helmert transformation cannot be applied;
- In precise positioning, users have to apply epoch (weekly or monthly) positions as a reference instead of those derived from a reference epoch and (a sequence of) velocities.

Changes in the kinematics of the SIRGAS Reference Frame after the earthquake in February 2010 in Chile

Newly estimated station positions and velocities are compared with reference frames computed previous to the Chile earthquake, namely with ITRF2008 and the SIR10P01 cumulative SIRGAS solution for the year 2010 (covering the time span from January 2000 to January 2010). These comparisons show very large discrepancies (Fig. 4 and 5), in particular in the East component. Main reasons for this disagreement are:

- ITRF2008 and SIR10P01 do not reflect the effects (co-seismic and post-seismic movements) caused by the earthquake in February 2010 ;
- The weekly input solutions for ITRF2008 and SIR10P01 were computed with respect to the IGS05 frame, while the new solution is computed with respect to IGS08/IGb08;
- Troposphere effects in SIR10P01 and the new solution 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 stations located in the tropical region;
- The uncertainty of the station velocities reduces the reliability of the station positions in the new solution, since an extrapolation from 2012.0 (reference epoch) to 2005.0 (epoch for comparison with the other solutions) is necessary;
- The datum realisation in both solutions is based on different fiducial points. While the old solution includes reference stations located in Latin America only, the new solution comprises reference stations located far away.

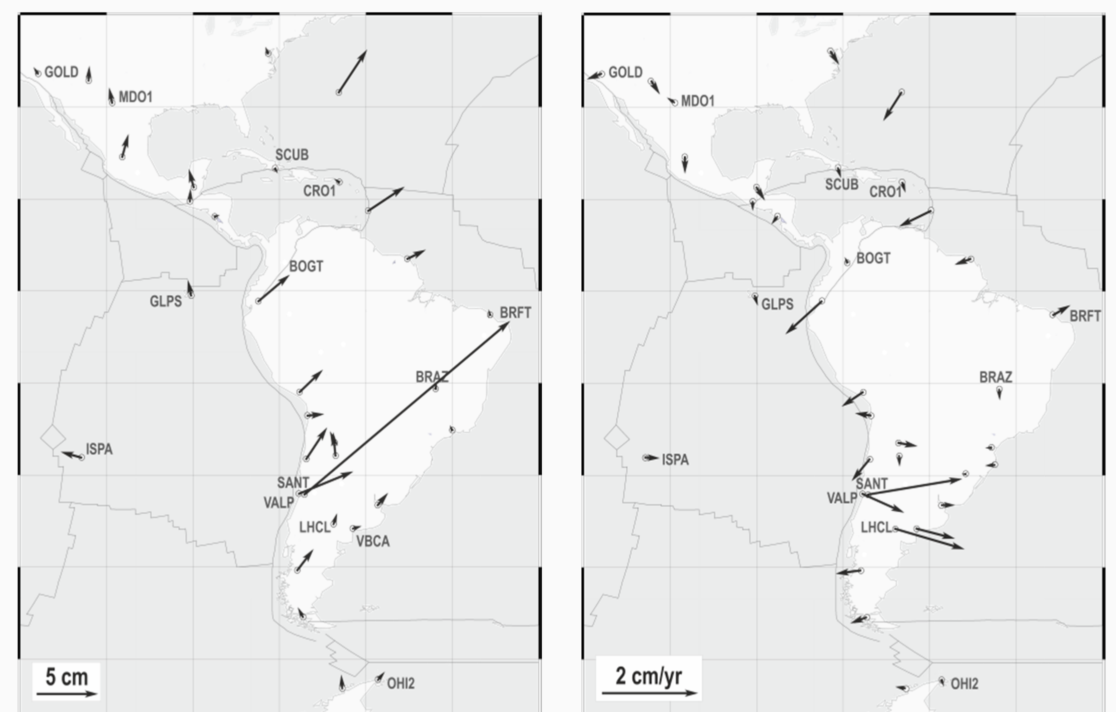

Fig. 4. Horizontal position difference vectors (left) and horizontal velocity difference vectors (right) between ITRF2008 and the post-seismic solution (all station coordinates refer to epoch 2005.0).

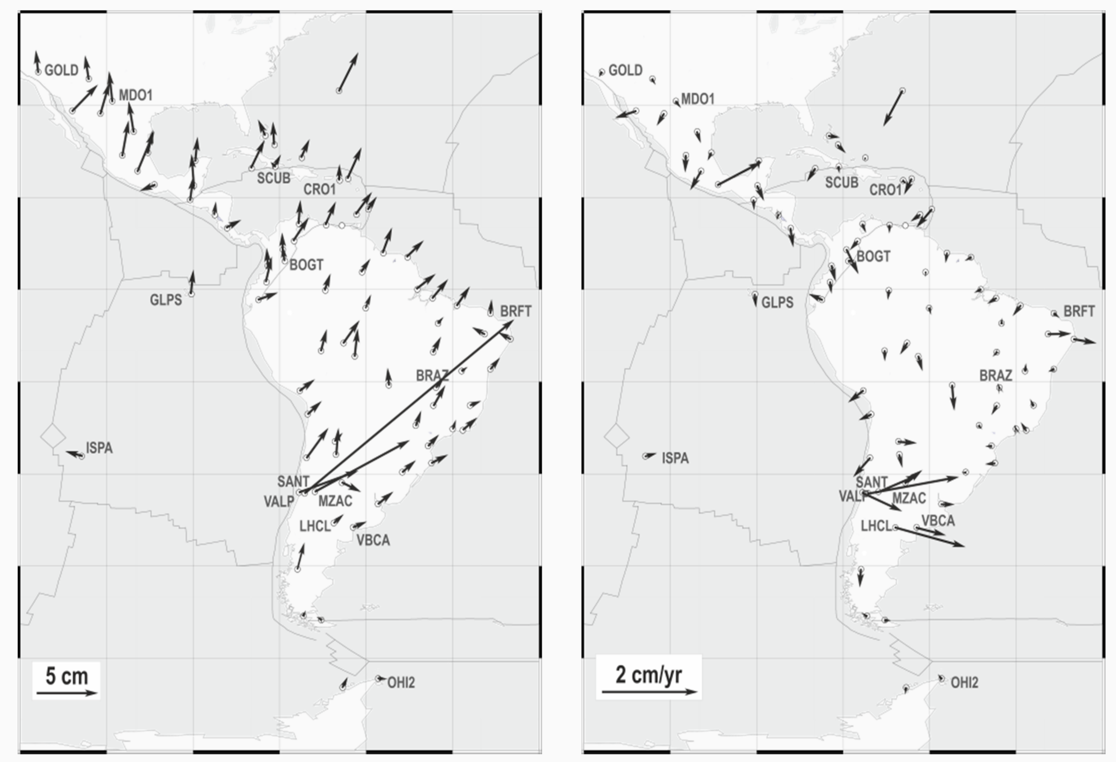

Fig. 5. Horizontal position difference vectors (left) and horizontal velocity difference vectors (right) between SIR10P01 (before the earthquake in February 2010) and the post-seismic solution (all station coordinates refer to epoch 2005.0).

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