The Velocity Model for SIRGAS 2010-2015 (VEMOS2015)

Hermann Drewes and Laura Sánchez

International Association of Geodesy (IAG)
Deutsches Geodäatisches Forschungsinstitut
Technische Universität München (DGFI-TUM)

Symposium SIRGAS, Quito, Ecuador, 16-18 November 2016
The standard tectonic models distinguish tectonic plates and deformation zones (orogenes).

**Plates:**
- NA  N America
- AF  Africa
- RI  Rivera
- CA  Caribbean
- PM  Panama
- ND  North Andes
- CO  Cocos
- GP  Galapagos
- PA  Pacific
- EA  Easter Island
- NZ  Nazca
- AP  Altiplano
- SA  S America
- JZ  Juan Fernandez
- AN  Antarctica
- SC  Scotia

**Orogenes:**
- WCA  West Central Atlantic
- PRU  Peru
- PSP  Puna-Sierras Pampeanas
Earthquakes in the SIRGAS region since January 2010 with magnitudes > 5

The interaction of these moving tectonic units causes a very high seismic activity (earthquakes) which generates episodic crustal movements and long-term crustal deformation affecting geodetic reference frames (ITRF, continental densification SIRGAS and all the national densifications).

*Earthquakes with magnitudes > 5 in Latin America and the Caribbean from January 2010 to April 2015. Source: IRIS: Incorporated Research Institutions for Seismology, www.iris.edu*
Seismic deformations in reference frames (e.g. SIRGAS)

The precise determination and modelling of the co-seismic and post-seismic displacements and changes in the surface velocities over the entire affected area is necessary to guarantee:

1) The reliability of all the positions in the adopted reference frame estimated for the week when a seismic event occurs;

2) The appropriate transformation between the pre-seismic and the post-seismic (deformed) reference frame;

3) The long-term stability of the geodetic reference frames to be obtained by the corrections of the seismic displacements.

Co-seismic displacements caused by the large earthquakes in Chile (Feb. 2010) and in Guatemala (Nov. 2012)
Input data: velocities based on cumulative solutions of GNSS weekly normal equations

- Weekly normal equations (according to IERS/IGS/SIRGAS standards);
- Time span: 2010.2 (2012.2) - 2015.2; 471 stations;
- Frame: IGb08 epoch 2013.0; Accuracy: N - E = ±1.0 mm/a, h = ±1.2
Input data: velocities based on cumulative solutions of GNSS weekly normal equations
Pre-seismic and post-seismic (deformed) reference frames

Reference networks without deformation:

Reference networks with deformation:
Modelling of deformations based on the geodetic Least Squares Collocation Approach (LSC)

2D-vector prediction:

\[ \mathbf{v}_{\text{pred}} = \mathbf{C}_{\text{new}}^T \mathbf{C}_{\text{obs}}^{-1} \mathbf{v}_{\text{obs}} \]

\( \mathbf{v}_{\text{pred}} \) = predicted velocities \((v_N, v_E)\) in a \(1^\circ \times 1^\circ\) grid

\( \mathbf{v}_{\text{obs}} \) = observed velocities \((v_N, v_E)\) in geodetic stations

\( \mathbf{C}_{\text{new}} \) = correlation matrix between predicted and observed vectors

\( \mathbf{C}_{\text{obs}} \) = correlation matrix between observed vectors \((C_{NN}, C_{EE}, C_{NE})\)

\( \mathbf{C} \) matrices are built from empirical isotropic, stationary covariance functions.
Deformation model based on a geodetic Least Squares Collocation Approach (LSC)

To satisfy the isotropy condition, the plate motions \[ \mathbf{v} = \Omega(\Phi, \Lambda, \omega) \times \mathbf{X} \] are reduced from observations:

\[
\begin{align*}
(d\varphi/dt)_k &= \omega_i \cdot \cos \Phi_i \cdot \sin(\lambda_k - \Lambda_i) \\
(d\lambda/dt)_k &= \omega_i \cdot (\sin \Phi_i - \cos(\lambda_k - \Lambda_i) \cdot \tan \varphi_k \cdot \cos \Phi_i)
\end{align*}
\]

Comparison of rotation vectors \( \Omega \)

<table>
<thead>
<tr>
<th>Plate</th>
<th>( \Phi [^\circ] )</th>
<th>( \Lambda [^\circ] )</th>
<th>( \omega [\text{mas/a}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA(VEMOS15)</td>
<td>(-0.2 \pm 1.0)</td>
<td>270.1 ± 1.1</td>
<td>0.82 ± 0.03</td>
</tr>
<tr>
<td>APKIM2008</td>
<td>-5.8 ± 0.5</td>
<td>272.5 ± 0.2</td>
<td>0.68 ± 0.01</td>
</tr>
<tr>
<td>CA(VEMOS15)</td>
<td>26.4 ± 0.9</td>
<td>270.4 ± 2.2</td>
<td>1.21 ± 0.07</td>
</tr>
<tr>
<td>APKIM2008</td>
<td>28.0 ± 1.3</td>
<td>250.9 ± 2.7</td>
<td>0.75 ± 0.06</td>
</tr>
<tr>
<td>NZ(VEMOS15)</td>
<td>44.1 ± 1.3</td>
<td>258.0 ± 0.3</td>
<td>2.21 ± 0.02</td>
</tr>
<tr>
<td>APKIM2008</td>
<td>45.9 ± 0.6</td>
<td>257.6 ± 0.3</td>
<td>2.28 ± 0.02</td>
</tr>
<tr>
<td>SA(VEMOS15)</td>
<td>-22.2 ± 0.6</td>
<td>226.9 ± 1.7</td>
<td>0.44 ± 0.01</td>
</tr>
<tr>
<td>APKIM2008</td>
<td>-19.4 ± 1.0</td>
<td>237.8 ± 1.5</td>
<td>0.46 ± 0.01</td>
</tr>
</tbody>
</table>

... smaller blocks
... deformation zones

After the collocation procedure, the plate motions are added to the interpolated velocities again (remove–restore).
Observed and predicted velocities
Deformation relative to the Caribbean Plate
Deformation relative to the South American Plate

VEMOS 2009

VEMOS 2015
Differences with previous deformation models

VEMOS 2015 - VEMOS 2009

Many new data after earthquakes in Costa Rica and Guatemala 2012

VEMOS 2015 – VEMOS 2014

Longer time span and new data available
Transformation between pre- and post-seismic frames

Transformation based on VEMOS 2009

Transformation based on VEMOS 2015

Earthquake

Modelling co-seismic displacements & post-seismic relaxation

\[ t_1 \quad t_2 \quad t_3 \quad t_4 \quad t_5 \quad t \]
Co-seismic displacements and velocity changes

Displacement at earthquake 2010

Velocity change after event 2010
Conclusions

- The earthquakes in Latin America since 2010 produced co-seismic displacements of up to 3 m in the SIRGAS reference frame.
- The surface velocity field in Central and South America has changed dramatically after these seismic events.
- Consequently the involved countries cannot use the official national reference frame (referring to the pre-seismic epoch) for scientific studies and practical applications.
- The predicted 1° x 1° velocity grid allows the interpolation of station positions and velocities in the considered time span (2011-2015) and transformations to previous epochs.
- The co-seismic displacement has to be modelled (→ MoNoLin)
- The computation of the velocity field has to be repeated until the velocities have come to a “normal” behaviour. This may take years.
- Thank you very much for your attention!