The Velocity Model for SIRGAS 2010-2015 (VEMOS2015)

Hermann Drewes and Laura Sánchez

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

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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
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 study and fix:

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.
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 mm/a
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°×1° 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 \[ \mathbf{v} = \mathbf{\Omega}(\Phi, \Lambda, \omega) \times \mathbf{X} \] are reduced from observations:

\[ \frac{d\varphi}{dt} = \omega_i \cdot \cos \Phi_i \cdot \sin(\lambda_k - \Lambda_i) \]
\[ \frac{d\lambda}{dt} = \omega_i \cdot (\sin \Phi_i - \cos(\lambda_k - \Lambda_i) \cdot \tan \varphi_k \cdot \cos \Phi_i) \]

<table>
<thead>
<tr>
<th>Plate</th>
<th>( \Phi ) [°]</th>
<th>( \Lambda ) [°]</th>
<th>( \omega ) [mas/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA (VEMOS15)</td>
<td>-0.2 ± 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

VEMOS 2015 – VEMOS 2014

Many new data after earthquakes in Costa Rica and Guatemala 2012

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

Transformation based on VEMOS 2009

Transformation based on VEMOS 2015

Modelling co-seismic displacements & post-seismic relaxation
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!
¡Muchas gracias por su atención!