Surface kinematics in the Alpine-Carpathian-Dinaric and Balkan region inferred from a new multi-network GPS combination solution

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Some history

- Several Presentations at EUG (invited paper at CEI session), EUREF Symposium, WEGENER meeting and others
- Editor response on 23.05.2007: paper interesting, but too many things irrelevant to geodynamics;
- Discussions among us on what to do result in decision of extracting the purely geodynamic part leaving the more geodetic part to a separate paper
- AC circulates on 09.10.2007 a radically revised version. Emphasis on velocity flow and geokinematic interpretation.
- Invitation from Topoeurope on 02.10.2007 to submit a contributed paper on a special issue of Tectonophysics with deadline January 15, 2008
- Reasonable strategy: submit the CERGOP2 paper now; work on an improved paper including reprocessing, CEGRN06/07, other regional SINEX to submit to Tectonophysics
- 10.10.2007: Title ‘Geokinematics of Central Europe inferred from the CEGRN GPS network’ was submitted, with extended authors (Connie and Sandro) in time for deadline of Oct. 15.
- 10.01.2008: final acceptance of J of Geody CERGOP 2 paper
- 03.09.2008: Revision 1 submitted to Tectonophysics emphasis on combination/geodesy
- 04.04.2009: Revision 2 submitted to Tectonophysics: several references added
- 07.04.2009: informal communication of paper final acceptance
CEGRN Team and the scientific exploitation of geodetic data

CEGRN= Central European Geodynamic Research Network [http://www.fomi.hu/CEGRN/]

• Funded under the FP5
• *Geokinematics of Central Europe: New insights from the CERGOP-2/Environment Project*
• *Surface kinematics in the Alpine-Carpathian-Dinaric and Balkan region inferred from a new multi-network GPS combination solution*
  Tectonophysics, In Press, Accepted Manuscript, Available online 5 May 2009
• Active contribution to the EUREF/IAG Special project on Dense Velocity Fields
Key elements of the Tectonophysics/Topoeurope work (1/2)

- **CEGRN Campaigns Reprocessing!**

<table>
<thead>
<tr>
<th>Software</th>
<th>Bernese 5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>A priori coordinates</td>
<td>ITRF2005 coordinates and velocities</td>
</tr>
<tr>
<td>minimum constraints (no net translation) at the sites BOR1 GRAZ JOZE KOSG LAMA METS ONSA PENC ZIMM WTZR MATE GOPE</td>
<td></td>
</tr>
<tr>
<td>Datum definition</td>
<td></td>
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<tr>
<td>Absolute Phase Center Variations</td>
<td></td>
</tr>
<tr>
<td>Elevation cutoff</td>
<td>5 degrees</td>
</tr>
<tr>
<td>Elevation dependent weighting</td>
<td>Applied</td>
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<tr>
<td>Station information file</td>
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<tr>
<td>Ocean loading corrections</td>
<td>FES2004</td>
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<td>Earth Orientation Parameters, Orbits and satellite information</td>
<td>Potsdam Munich Dresden reprocessing</td>
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<tr>
<td>Frame for orbits</td>
<td>IGS00b</td>
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</tbody>
</table>
Key elements of the Tectonophysics/Topoeurope work (2/2)

- Combination of 7 networks in RV space

1. AMON
2. ARE
3. CEGRN
4. EUREF
5. SK
6. UPA
7. YUK
Issues on combining multi-year cumulative solutions in RV space

• Input SINEX are inhomogeneous as to:
  – Processing standards: different reference frames co-exist, absolute/relative antenna models, el-cutoff, ways to impose constraints, orbits/EOP’s...
  – Each combination group originating a RV SINEX may have made own choices as to soln’s

• As a conclusion, the slope (velocity) in time series are probably OK, but the coordinates may be inconsistent

• For the sake of geokinematics, velocities are really important, coordinates not so much

• Reprocessing would solve all the pending issues!
ADDNEQ2 combination of 7 normal equations results in 466 homogeneous velocities, same ITRF2005 frame

- SUMMARY OF RESULTS
  - Number of parameters:
    - Station coordinates / velocities: 2905
    - Site-specific troposphere parameters: 522
    - Previously pre-eliminated parameters: 36081485
    - Total number: 36084912

- Statistics:
  - Total number of explicit parameters: 2803
  - Total number of implicit parameters: 36082109
  - Degree of freedom (DOF): 241400246
  - A posteriori RMS of unit weight: 0.00272 m
  - Chi**2/DOF: 7.41

<table>
<thead>
<tr>
<th>Station</th>
<th>rms (m)</th>
<th>Tx (m)</th>
<th>Ty (m)</th>
<th>Tz (m)</th>
<th>Rx (arcsec)</th>
<th>Ry (arcsec)</th>
<th>Rz (arcsec)</th>
<th>scale (ppm)</th>
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</thead>
<tbody>
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<tr>
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<td>0.0017</td>
<td>0.0002</td>
<td>0.0001</td>
<td>0.00432</td>
</tr>
</tbody>
</table>

Minimum constraints on coordinates ITRF2005; high constraints on ITRF2005 velocities
Interpolation of velocities by least squares collocation

\[
\begin{bmatrix}
    v_n \\
    v_{n'}
\end{bmatrix}
= \sum_s C(d_{p,s}) \sum_{s'} [C(d_{s,s'}) + W_{s,s'}]^{-1} \begin{bmatrix}
    v_n \\
    v_{n'}
\end{bmatrix}_{s',}
\]

\[
\begin{bmatrix}
    \sigma^2_n \\
    \sigma^2_{n'}
\end{bmatrix}_p = I \sigma^2 - \sum_s C(d_{p,s}) \sum_{s'} [C(d_{s,s'}) + W_{s,s'}]^{-1} C^T(d_{p,s'}) \begin{bmatrix}
    \sigma^2_n \\
    \sigma^2_{n'}
\end{bmatrix}_{s'}
\]

\[
W_{s,s'} = \frac{1}{\sigma^2_s} \delta_{s,s'}
\]

Correlation distance 250-350 km, same order of magnitude of the flexural parameter of a semiinfinite elastic, isostatically supported halfspace of thickness 30 km

Velocity profiles: Eastern Alps
Pannonian Basin

Blue: measured velocity
Red: velocities interpolated to the profile

Scale axis x: 100 km
Velocity profiles in the Adriatic and Albania

Right lateral shear (velocity changes sign)

Compression (velocity drop)
Modeling velocity inversion, locking depth ‘a’ and lithospheric thickness ‘b’ in a strike slip fault system

\[ u(x) = \Delta u \ln \left( \frac{\sinh \frac{\pi (x - \bar{x})}{2b}}{\sqrt{1 + \frac{\pi^2 a^2}{4b^2}}} \right) \]

\[ a = 24 +/- 3 \text{ km} \]
\[ b = 120 +/- 10 \text{ km} \]
Conclusions

• First attempt to combine Multi-year solutions to estimate a dense velocity field
• Experience gained in the technical aspects and open questions in this new type of combination
• Improved velocity field across Europe through Least Squares Collocation
• Improved picture in known areas (eastern Alps), new results on several other areas (Pannonian basin, Adria-Balkans)
• Average strain rate in highly seismic zones computed with improved resolution
Conclusion: how can geodesy better integrate with seismology for mitigation of seismic hazard?

- Identify seismic zones: homogeneous geology, CMT's, historical catalogue
- Evaluate $a$ and $b$ of Gutenberg Richter law from catalogue for each zone
- Evaluate the seismic volume based on $m$, local Yield Stress Envelope
- Evaluate seismically released strain (Kostrov)
- Compare with geodesy and interpret discrepancies - review strength envelope of the lithosphere

$$
\varepsilon_{Kostrov} = \frac{1}{2\mu} \int_{m_{min}}^{m_{max}} \frac{M_0(m)N(m)}{h(m)A(m)} \, dm
$$

$h = \text{depth of seismogenic volume: requires Yield Stress Envelope}$

$M_0 = \text{seismic moment released by individual event}$

$N = a + bm \quad \text{Distribution of Gutenberg - Richter}$

$A = \text{slip area}$

$m = \text{magnitudo}$