Real-time Precise Point Positioning supported with high-resolution troposphere models based on Numerical Weather Prediction

Tomasz Hadaś, Karina Wilgan, Paweł Hordyniec, Jarosław Bosy

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MOTIVATION (1)


\[ I_p = \frac{1}{f_1^2 - f_2^2} \left( f_1^2 P_1 - f_2^2 P_2 \right) = \rho + c(\delta t_r - \delta t^s) + \delta T_r^s + \epsilon_p \]

\[ I_\phi = \left[ \frac{1}{f_1^2 - f_1^2} \left( f_1^2 P_1 - f_2^2 P_2 \right) \right] \lambda_{L3} = \rho + c(\delta t_r - \delta t^s) + \delta T_r^s + N\lambda_{L3} + \epsilon_\phi \]

Drawbacks:

• troposphere is a major error source
• ZTD is highly correlated with \( U_r \) and \( \delta t_r \)
• long convergence time

Solution:

• introduce high-res tropo model
• \( U_r \) and \( \delta t_r \) are highly correlated
• shorter convergence time
**MOTIVATION (2)**

**Standard approach:**
- ZHD from external model as fixed value
- ZWD estimated as random walk process

**Troposphere constraining (post-proc):**
- a priori ZTD from external model (first epoch)
- ZWD estimated as random walk process
- additional equation in functional model:
  \[
  \delta ZTD = ZTD^{NRT} - ZTD'
  \]
  \(ZTD^{NRT}\) - the zenith troposphere delay from near real-time regional model
  \(ZTD'\) - the a priori zenith troposphere delay value (from previous epoch)
  \(\delta ZTD\) - the correction to the a priori zenith troposphere delay value
DATA

NRT GNSS

- near real-time ZTD and Hz gradients
- 272 stations from Poland and adjacent area
- ZTD with 1-h resolution
- ~6 mm accuracy

NWP WRF

- WRF – Weather Research & Forecasting
- 4x4 km² grid
- 47 vertical levels
- forecasts at 0:00, 6:00, 12:00, 18:00 UTC
- total refractivity (N) from p, T, e with 1-h resolution (coefficients Rüeger `best average’):

\[ N_{tot} = k_1 \frac{p-e}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2} \]
3 test periods:
1. standard: Dec 2 – 8, 2015
2. calm: May 2 – 8, 2016

14 test stations (EPN) excluded from building the model
Real-time ZTD - methodology

\[ l = f(u, x, t) + s(C_{ss}, x, t) + n \]

Least-squares collocation using software COMEDIE developed at ETH Zürich

Zenith total delay (from NRT GNSS)

\[ ZTD(x, y, z, t) = (ZTD_0 + a_{ZTD}(x - x_0) + b_{ZTD}(y - y_0) + c_{ZTD}(t - t_0)) \cdot e^{\frac{z}{H_{ZTD}}} \]

Total refractivity (from WRF)

\[ N(x, y, z, t) = \frac{1}{H_{ZTD}}(ZTD_0 + a_{ZTD}(x - x_0) + b_{ZTD}(y - y_0) + c_{ZTD}(t - t_0)) \cdot e^{\frac{z}{H_{ZTD}}} \]

Real-time ZTD - results

Comparison of ZTDs obtained from 3 models (RT COMEDIE, VMF1-FC, UNB3m) w.r.t. EPN

$\sigma=10\text{mm}$

(RT vs EPN)
MAPPING FUNCTION (WRFMF) - METHODOLOGY

- the methodology based on VMF ‘fast’ approach\(^1\)
- hydrostatic b,c → from Isobaric Mapping Function:
  \[ b_h = 0.002905 \]
  \[ c_h = 0.0634 + 0.0014 \cdot \cos(2\varphi) \]
- wet b,c → from Niell Mapping Function:
  \[ b_w = 0.00146 \]
  \[ c_w = 0.04391 \]
- WRF ray-tracing (every 1 h) for \( el=3.3^\circ \) → SHD/SWD, ZHD/ZWD
  \[ MF_h = (SHD + d_{geo})/ZHD \]
  \[ MF_w = SWD/ZWD \]
- a-coefficients from inverting the continued fraction → WRFMF

Mapping Function (WRFMF) - results

Comparison of the hydrostatic and wet MFs from three models: WRFMF, VMF1-FC and UNB3m; station ZYWI; cut-off angle in processing 5°
PPP STRATEGY

In house developed GNSS-WARP software:
- GPS PPP (L1/L2 iono-free)
- float ambiguities, IGS03 stream
- 3 types of coordinates (see Figure)
- 6 processing variants (see Table)

<table>
<thead>
<tr>
<th>ZTD</th>
<th>Constr.</th>
<th>MF</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNB3M</td>
<td>NONE</td>
<td>UNB3M</td>
</tr>
<tr>
<td>VMF1-FC</td>
<td>NONE</td>
<td>VMF1-FC</td>
</tr>
<tr>
<td>WRF</td>
<td>NONE</td>
<td>WRFMF</td>
</tr>
<tr>
<td>COMEDIE</td>
<td>10 mm</td>
<td>UNB3M</td>
</tr>
<tr>
<td>COMEDIE</td>
<td>10 mm</td>
<td>VMF1-FC</td>
</tr>
<tr>
<td>COMEDIE</td>
<td>10 mm</td>
<td>WRFMF</td>
</tr>
</tbody>
</table>
### 3D Coordinate bias

<table>
<thead>
<tr>
<th></th>
<th>3D Bias [mm]</th>
<th>3D StdDev [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNB3m</td>
<td>32.6</td>
<td>4.6</td>
</tr>
<tr>
<td>VMF1-FC</td>
<td>35.0</td>
<td>4.7</td>
</tr>
<tr>
<td>WRFMF</td>
<td>46.4</td>
<td>4.6</td>
</tr>
<tr>
<td>COMEDIE-UNB3m</td>
<td>14.9</td>
<td>6.3</td>
</tr>
<tr>
<td>COMEDIE-VMF1-FC</td>
<td>14.2</td>
<td>6.3</td>
</tr>
<tr>
<td>COMEDIE-WRFMF</td>
<td>12.9</td>
<td>6.4</td>
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### 3D Coordinate StdDev

<table>
<thead>
<tr>
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<th>3D StdDev [static (mm)]</th>
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<tbody>
<tr>
<td>UNB3m</td>
<td>3D StdDev (static) [mm]</td>
</tr>
<tr>
<td>VMF1-FC</td>
<td>3D StdDev (static) [mm]</td>
</tr>
<tr>
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</tr>
<tr>
<td>COMEDIE-UNB3m</td>
<td>3D StdDev (static)</td>
</tr>
<tr>
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</tr>
<tr>
<td>COMEDIE-WRFMF</td>
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</tr>
</thead>
<tbody>
<tr>
<td>UNB3m</td>
<td>25.2</td>
<td>104.4</td>
</tr>
<tr>
<td>VMF1-FC</td>
<td>27.5</td>
<td>104.2</td>
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<tr>
<td>WRFMF</td>
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<td>103.8</td>
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<tr>
<td>COMEDIE-UNB3m</td>
<td>14.2</td>
<td>105.9</td>
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<tr>
<td>COMEDIE-VMF1-FC</td>
<td>14.7</td>
<td>106.4</td>
</tr>
<tr>
<td>COMEDIE-WRFMF</td>
<td>15.9</td>
<td>108.3</td>
</tr>
</tbody>
</table>

### 3D Coordinate StdDev

Residuals (estimated – EPN official)
**Convergence time (3-h reinitialized kinematic)**

Initialization time for 10 cm level of convergence (based on formal error):

<table>
<thead>
<tr>
<th></th>
<th>UNB/VMF</th>
<th>COMEDIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hz (N/E)</td>
<td>67 min</td>
<td>58 min</td>
</tr>
<tr>
<td>V (Up)</td>
<td>79 min</td>
<td>63 min</td>
</tr>
</tbody>
</table>

Percentage of converged solutions during the 3-h reinitialization period for 10 cm level of convergence:

<table>
<thead>
<tr>
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<th>COMEDIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hz (N/E)</td>
<td>99%</td>
<td>100%</td>
</tr>
<tr>
<td>V (Up)</td>
<td>76%</td>
<td>88%</td>
</tr>
</tbody>
</table>
SUMMARY

- RT PPP in 6 processing variants (different combinations of a priori ZTD and MFs), 3 time-periods
- 3 types of coordinates: static, continuous kinematic and reinitialized kinematic
- ZTD constraining with NWP:
  - pros: better accuracy (< bias), shorter convergence time
  - cons: slightly worse precision (> standard deviations)

Wilgan K., Hadaś T., Hordyniec P., Bosy J. (2017): Real-time precise point positioning augmented with high-resolution numerical weather prediction model. GPS Solutions 23(3), 1341-1353
Thank you for your attention!

Questions?

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