Refined and site-augmented tropospheric delay models for GNSS applications

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\[ \Delta L(e) = \Delta L_h^z \cdot m_{f_h}(e) + \Delta L_w^z \cdot m_{f_w}(e) \]

- \( \Delta L^z \): from IGS
- \( \Delta L_h^z \): calculated from \( p \) (measured or taken from models)
- \( \Delta L_w^z \): calculated via \( \Delta L^z - \Delta L_h^z \)
- \( m_{f_h}, m_{f_w} \): from real-time mapping functions such as VMF1

**BUT:** Many applications without access to data from NWM or IGS

\[ \Rightarrow \text{empirical troposphere models} \]
Global Pressure and Temperature 2 wet (Böhm et al., 2015)

Empirical (blind) troposphere model providing:

\[ \Delta L_w^z = 10^{-6} \times \left( k'_2 + \frac{k_3}{T_m} \right) \times \frac{R_d e}{(\lambda + 1) g_m} \]

Can we improve the empirical \( \Delta L_w^z \) by including in situ measured meteorological data?

formula of Askne and Nordius (1987)
Augmentation of $\Delta L_w^z$

- no in situ measurements (= empirical only)
  \[ \Delta L_w^z = L_w^{GPT2w} \]

- in situ measurement of $T$
  \[ \Delta L_w^z = L_w^{GPT2w} + M \ast (T_{GNSS} - T_{GPT2w}) \]

- in situ measurement of $T$ and $e$
  a.) \[ \Delta L_w^z = L_w^{GPT2w} + M_1 \ast (T_{GNSS} - T_{GPT2w}) + M_2 \ast (e_{GNSS} - e_{GPT2w}) \]
  b.) \[ \Delta L_w^z = 10^{-6} \ast \left( k_2' + \frac{k_3}{T_{m,GPT2w}} \right) \ast \frac{R_d e}{(\lambda_{GPT2w} + 1)g_m} \]
Augmentation of $\Delta L^z_w$

Refined and site-augmented tropospheric delay models for GNSS applications (Landskron et al., 2016)

If user measures $T$ and $e$ => improve $\Delta L^z_w$:

$$\Delta L^z_w = L^z_{w_GPT2w} + M_1 \times (T_{GNSS} - T_{GPT2w}) + M_2 \times (e_{GNSS} - e_{GPT2w})$$

Overall correlations:
- $T$ with $\Delta L^z_w$: 0.65
- $e$ with $\Delta L^z_w$: 0.85

Correlation plots for BZRG

Universal, global coefficients $M_1$, $M_2$:
- $M_1 = 5 \times 10^{-4}$ [m/°C⁻¹]
- $M_2 = 0.0092$ [m/hPa⁻¹]
Data

**GNSS Data:**
- 55 globally distributed IGS stations
- 4 epochs per day in 2013
- zenith total delay ($\Delta L^z$) from IGS final tropospheric SNX-TROPO

**Meteo Data:**
- $p$, $T$, $e$ from
  1) close-by weather stations (provided by ZAMG, blue dots)
    - max. 10km ↔ and 100m ↑ away
    - high quality
  2) in-situ measurements (provided by IGS, pink dots)
    - moderate quality

\[
p \Rightarrow \text{Extrapolation} / \text{Saastamoinen} \Rightarrow \Delta L^z_h
\]
\[
\Delta L^z_w = \Delta L^z - \Delta L^z_h \Rightarrow \text{Considered as "true" values}
\]
Comparison of $\Delta L_w^z$ for BZRG
Comparison of $\Delta L_w^z$ for BZRG
Comparison of $\Delta L_w^z$ for BZRG
Comparison of $\Delta L_w^z$ for BZRG
Comparison of $\Delta L_w^z$ for ALIC
Results

Comparison of $\Delta L_w^z$ for ALIC
Comparison of $\Delta L^z_w$ for ALIC
Results

Comparison of $\Delta L_w^z$ for ALIC

IGS
GPT2w
GPT2w + T
GPT2w + T, e (a)
GPT2w + T, e (b)
Comparison of $\Delta L_w^z$ for NYA1
Results

Comparison of $\Delta L_w^z$ for NYA1
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Results

Refined and site-augmented tropospheric delay models for GNSS applications (Landskron et al., 2016)
Results

Comparison of “true” $\Delta L_w^z$ from IGS with reproduced $\Delta L_w^z$: 

- Mean absolute difference in $\Delta L_w^z$ (averaged over all stations and epochs)

<table>
<thead>
<tr>
<th></th>
<th>$\Delta L_w^z$ [cm]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>empirical only (= GPT2w)</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>empirical + T</td>
<td>2.7</td>
<td>2.6</td>
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<tr>
<td>empirical + T and e (a)</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>empirical + T and e (b)</td>
<td>2.0</td>
<td>2.1</td>
</tr>
</tbody>
</table>

\[
\text{Corr. Coeff. (a)} = \text{mean}(|\Delta L_{wIGS}^z - \Delta L_{wGPT2w}^z|)\\
\text{Corr. Coeff. (b)} = \text{mean}(|\Delta L_{wIGS}^z - \Delta L_{wGPT2w}^{\text{mod}(2)}|)\\
\text{Corr. Coeff. (a)} = \text{mean}(|\Delta L_{wIGS}^z - \Delta L_{wGPT2w}^{\text{mod}(3\omega)}|)\\
\text{Corr. Coeff. (b)} = \text{mean}(|\Delta L_{wIGS}^z - \Delta L_{wGPT2w}^{\text{mod}(3b)}|)
\]

- Correlation coefficient (averaged over all stations and epochs)

<table>
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<th>Corr. Coeff. (a)</th>
<th>Corr. Coeff. (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>empirical only (= GPT2w)</td>
<td>0.70</td>
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<td>empirical + T</td>
<td>0.73</td>
<td>0.76</td>
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<tr>
<td>empirical + T and e (a)</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>empirical + T and e (b)</td>
<td>0.86</td>
<td>0.86</td>
</tr>
</tbody>
</table>

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Conclusions

• GPT2w well suited for site-augmented approach using in situ measurements of $T$ and $e$
• in situ measurement of $T$ yields small improvement in zenith wet delay $\Delta L^z_w$ (~5%)
• additional in situ measurement of $e$ yields significant improvement in zenith wet delay $\Delta L^z_w$ (~30%)
  => not much difference which formula is used for $e$
• In general, best performance of site-augmented GPT2w is achieved in dry regions

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