Neutral Atmosphere and Geodesy

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Acknowledgement: Gregor Möller, Michael Schindelegger, ..
The Atmosphere ...

• .. does not only cause troubles ..
• .. but opens a wide range of possibilities for geodesy
The Atmosphere...

.. delays signals in the
  • ionosphere and
  • troposphere,

.. influences
  • **Earth rotation**,  
  • satellite orbits,  
  • Earth gravity field

.. moves points due to
  • loading and
  • thermal deformation.
The Atmosphere ...

.. delays signals in the
• ionosphere and
• **troposphere**,
Refractivity $N = N (p, T, e)$
Troposphere Delays

\[ \Delta L = L - G = \int_S n(s)ds - G \]
Troposphere Delays

\[ \Delta L_h^z = 0.0022768 \frac{p_0}{f(\theta, h_0)} \]

[Saastamoinen, 1972; Davis et al., 1985]

\[ \Delta L(e) = \Delta L_h^z \cdot mf_h(e) + \Delta L_w^z \cdot mf_w(e) \]

[Nilsson et al., 2013]
Pressure Values

- Observed values
  - at epoch
- Numerical weather models
  - every 6 hours
- Blind models
  - Berg (1948)
  - Hopfield (1969)
  - UNB3m, GPT2, ...

O'Higgins, Antarctica

3 hPa → 1 mm height

destructive effect of blind models with loading
\[ \Delta L(e) = \Delta L^z \cdot mf(e) \]
\[ \Delta L(e) = \Delta L^z \cdot mf(e) \]

<table>
<thead>
<tr>
<th>Partials</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Clocks</td>
<td>1</td>
</tr>
<tr>
<td>Height</td>
<td>$\sin(e)$</td>
</tr>
<tr>
<td>Zenith delay</td>
<td>$\approx mf(e)$</td>
</tr>
</tbody>
</table>

5 mm @ 5° elevation → 1 mm height
Mapping Functions

- Niell Mapping Functions
  - blind
- Isobaric Mapping Functions
- Vienna Mapping Functions 1
  - ECMWF analysis (6 h)
- Global Mapping Functions
  - ‘averaged VMF1’
  - blind
  - GPT2

Fortaleza (Brazil)
### GPT2 and GPT2w

<table>
<thead>
<tr>
<th>GPT2</th>
<th>GPT2w amendments</th>
</tr>
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<tbody>
<tr>
<td>2001-2010 monthly mean profiles from ERA-Interim (37 levels)</td>
<td>-</td>
</tr>
<tr>
<td>5° grid at mean ETOPO5 heights</td>
<td>1° grid</td>
</tr>
<tr>
<td>Mean, annual, semi-annual terms; phases estimated</td>
<td>-</td>
</tr>
<tr>
<td>Pressure, temperature, water vapour pressure, lapse rate and mapping function coefficients</td>
<td>mean temperature $T_m$ and water vapour decrease factor $\lambda$</td>
</tr>
</tbody>
</table>
Blind Model for $\Delta L_w^z$: GPT2w

- Water vapour decrease factor $\lambda$ estimated from ray-traced zenith wet delay

\[
T_m = \frac{\int_H^\infty \frac{e}{T} dz}{\int_H^\infty \frac{e}{T^2} dz} \quad e = e_s \left( \frac{p}{p_s} \right)^{\lambda+1}
\]

\[
\Delta L_w^z = 10^{-6} \left( k_2' + \frac{k_3}{T_m} \right) \frac{R_d e_s}{(\lambda + 1) g_m}
\]
Blind Model for $\Delta L_w^z$: GPT2w

- Water vapour decrease factor $\lambda$ estimated from ray-traced zenith wet delay

$$e = e_s \left( \frac{p}{p_s} \right)^{\lambda+1}$$

$\lambda$ semi-annual amplitude [ ]
Blind Model: GPT2w

- RMS differences w.r.t. IGS ZTDs about 3.4 cm on average
Ray-tracing

- Great potential but limitations with large number of GNSS observations
- Many active groups, e.g.,
  - GSFC, UNB, NICT, GFZ, GRGS, Vienna, ...
- GSFC has shown improvement for VLBI baseline length repeatabilities
GNSS Meteorology

- Ground based
  - precipitable water, tomography
- Space based
  - radio occultation
- Climate monitoring

Nilsson, 2011
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Angular Momentum vs. Torque Approach

(1) Conservation of angular momentum in total system (solid Earth + fluids)

(2) Torque approach considers fluids as external layers:
   “push-and-pull” interaction with solid Earth

[Schindelegger, 2014]
Torque Approach

Total torque of solid Earth \((s)\) on the atmosphere \((a)\)

\[
L^{(s)\rightarrow(a)} = -L^{(a)\rightarrow(s)} = L^e + L^m + L^f
\]

Ellipsoidal torque \hspace{2cm} Mountain torque \hspace{2cm} Friction torque

Local Torques
Geophysical Influences on LOD

[Schindelegger, 2014]
Geophysical Influences on LOD

Mass (pressure) or motion (wind) terms?

\[
\frac{a^4}{g} \int \int_{\text{surface}} p_s \cos^3 \phi d\lambda d\phi \quad \frac{a^3}{g} \int \int_{\text{volume}} u \cos^2 \phi d\lambda d\phi dp
\]
Atmospheric Excitation of Earth Rotation Important..

- for a better understanding of the system Earth
- E.g., prograde annual nutation

Michael Schindelegger
Atmospheric Excitation of Earth Rotation Important..

- .. for a better understanding of the system Earth
- .. as **boundary condition** for NWMs
- Predictions of Earth rotation based on NWM forecasts are of importance for **spacecraft tracking** (0.1 ms = 1.6 km @ Mars) and real time **GNSS orbits**
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Atmospheric Effects on the Earth Gravity Field

• De-aliasing products for CHAMP, GRACE, GOCE
• .. for an improved detection of hydrology

\[
\begin{align*}
\left\{ \frac{\Delta C_{nm}}{\Delta S_{nm}} \right\} &= \frac{a^2}{(2n + 1)Mg_0} \int \int \left[ p_s - \bar{p}_s \right] P_{nm}(\cos \theta) \begin{bmatrix} \cos m\lambda \\ \sin m\lambda \end{bmatrix} \, dS
\end{align*}
\]

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Atmospheric Loading

Radial Deformation $u_r$:

$$u_r = \int \int (p_s - p_{ref}) \cdot G_R(\psi) \cdot ds$$

- $p_s$: Surface pressure
- $p_{ref}$: Reference pressure
- $G_R$: Green’s functions

Wettzell (non-tidal, IB)  

[Wijaya et al., 2011]
Conclusions

• Atmospheric corrections as determined from Numerical Weather Models play an important role in space geodesy, i.e., for the Earth gravity field, Earth rotation and figure of the Earth.

• All parameters are available in real-time when determined from forecast data.

• However, more research has to be carried out to reach the goals of GGOS: 1 mm in position and 0.1 mm/year in velocity.
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THANKS FOR YOUR ATTENTION