Atmospheric Effects in Space Geodesy

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The atmosphere

- is not only causing troubles in space geodesy..
- but it opens up a wide field of challenging tasks.
The atmosphere

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

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

.. moves reference points by
  • surface loading and
  • thermal deformation.
The atmosphere

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

GNSS, satellite altimetry and Formosat-3/COSMIC combined VTEC map on day 202, 2007 at 9:00 UT.

[Mahdi Alizadeh]
Troposphere delays

Pressure, temperature, and humidity from numerical weather models

\[ D_L = 10^{-6} \left[ \int_S N(s) \, ds \right] + [S - G] \]
Troposphere delays

\[ D_L(e) = D_z \cdot m(e) = D_{zh} \cdot m_h(e) + D_{zw} \cdot m_w(e) \]

+ gradients
Precipitable water

Zenith wet delays at Wettzell

- Nilsson et al. (2011)
- from VLBI
Zenith delay – clock - height

Partial derivatives:

- **clock:** $= 1$
- **height:** $= \sin(e)$
- **zenith delay:** $\approx m(e)$

\[ D_L(e) = D_z \cdot m(e) \]
\[ D_L(e) = D_z' \cdot m(e)' \]
Rule of thumb

- The station height error is about 1/5 of the troposphere delay error at the lowest elevation (5°). *(MacMillan and Ma, 1994)*
Mapping functions

- **Vienna Mapping Functions 1**
  - from ECMWF data (6 h)
  - Böhm et al. (2006)
- **Niell Mapping Functions**
  - Niell (1996)
- **Global Mapping Functions**
  - ‘averaged VMF1’
  - Böhm et al. (2006)

Fortaleza (Brazil)

[Böhm et al., 2006]
Vienna Mapping Functions VMF1

~21 ECMWF pressure levels: T, $p_{wv}$, h
interpolation
ray-tracing
(e = 90° and e = 3.3°)
Vienna Mapping Functions VMF1

\[ m(e) = \frac{a}{\sin(e) + \left( \frac{1 + \frac{b}{1 + \frac{c}{a}}}{1 + \frac{b}{\sin(e) - c}} \right)} \]

ray-tracing

variable in time and space

analytical functions
Height changes: GMF vs. VMF1 (hyd.)

Bias

Standard deviation

(Fund et al., 2011)
Hydrostatic zenith delays

\[ D_L(e) = D_z \cdot m(e) = D_{zh} \cdot m_h(e) + D_{zw} \cdot m_w(e) + \text{gradients} \]
Hydrostatic zenith delays

- pressure at the site
- numerical weather model
- Berg (1948)
- Global Pressure and Temperature (GPT)
  - Böhm et al. (2007)

O’Higgins (Antarctica)

[Böhm et al., 2007]
Influence on vertical velocities

GPT - ECMWF
- Antarctica
- 2003-2008
- Importance for Glacial Isostatic Adjustment (GIA)
- [King et al., 2011]
Availability of VMF1

Analysis (AN) and Prediction (FC) times for last observation for the prediction and time of availability.
AN vs. FC
Height std.dev. after 42 hours

VMF1 hyd.

VMF1 wet
Ray-traced slant delays

Tsukuba, 12 August 2008

Elevation

Azimut

0° 360°

[0 mm] [30 mm] [60 mm] [Nafisi, 2011]
Ray-traced slant delays

**Successful applications:**

- *Hobiger et al. (2008)* for PPP solutions w.r.t. GMF
- *MacMillan/Petrov* for VLBI w.r.t. VMF1
- *Hulley and Pavlis (2007)* for SLR
- *Böhm et al. (2010)* for VLBI Intensive sessions
- ...
Zenith delays estimated
No gradients estimated

Ray-traced delays better for 33 baselines

ECMWF/VMF1 better for 19 baselines
New twin telescopes Wettzell
VLBI2010 Simulations

Simulations

- fast 12m telescopes
- twin telescopes

Troposphere is limiting factor!

[Petrichenko et al., 2009]
VLBI2010 simulations
turbulence vs. clocks

(Pany et al 2009)
Troposphere delay modeling

• is the most **important error source** for the determination of the terrestrial reference frame (TRF)

• ... and **simulations based on turbulence** show that it will stay the critical factor in future, at least for microwave techniques.
Troposphere delay modeling

• **Ray-traced delays** have good prospects, but presently global numerical weather models are not yet accurate enough.

• The best troposphere delay models available need to be applied for **geophysical studies**.
The atmosphere

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

.. influences
• Earth rotation,
• satellite orbits,
• gravity field, and
Excitation of Earth rotation

Euler-Equation:

\[ \dot{\mathbf{L}} + \mathbf{\omega} \times \mathbf{L} = \mathbf{D} \]

- \( \mathbf{L} \) Angular momentum vector
- \( \mathbf{\omega} \) Earth rotation vector
- \( \mathbf{D} \) ext. torque vector (=0)

AAMF:

Atmosphere Angular momentum functions:
Mass- and wind terms
Geophysical influences on UT1

modified from ftp://gemini.gsfc.nasa.gov/pub/core/fig1.ps
Geophysical influences on UT1

modified from ftp://gemini.gsfc.nasa.gov/pub/core/fig1.ps
Geophysical influences on polar motion

nach ftp://gemini.gsfc.nasa.gov/pub/core/fig1.ps
Importance of AAMF

• Better understanding of the System Earth.
• Forecast atmospheric excitation for Spacecraft Tracking (0.1 ms = 1.6 km @ Mars) and predicted or real time GNSS orbits.
Gravity field
Gravity field

Surface pressure
- 1 January 2008
- Reference pressure removed

Geoid height change
- up to degree 100 from reduced surface pressure

[Maria Karbon]
The Atmosphere

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

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

...moves reference points by
• surface loading and
• thermal deformation.
Atmospheric loading

Radial deformation $u_r$:

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

- $p_s$: surface pressure
- $p_{\text{ref}}$: reference pressure
- $G_R$: Green’s functions
Atmospheric loading

[Wijaya et al., 2011]
[Petrov and Boy, 2004]
Tidal atmosphere loading: amplitudes

[S1 radial] 2mm [S2 radial] 2mm

[Wijaya, 2011]
Visions

• **Atmospheric corrections play a key role** in all fields of geodesy: Gravity, Rotation, and Figure of the Earth.

• However, more efforts will be necessary to reach the **one millimeter goal of GGOS**.

• Only then, **Global Change** can be assessed with sufficient accuracy, like sea level rise, ice melting at the poles, land hydrology, etc.
Thanks for your attention!
Backup slides
Implication on atmosphere loading

true pressure (ECMWF): 1020 hPa
mean pressure (GPT): 1000 hPa

loading: 8 mm
$\Delta D_{hz}$: $-46 \text{ mm}$
m(e): $+28 \text{ mm @5°}$

$\Delta$ height: 5.5 mm
Repeatabilities of station heights

no atmospheric loading correction

(Steigenberger et al., 2009)
Repeatabilities of station heights

<table>
<thead>
<tr>
<th>Method</th>
<th>No Atmospheric Loading Correction</th>
<th>A Posteriori Loading Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECMWF</td>
<td>8.0 mm</td>
<td>9.0 mm</td>
</tr>
<tr>
<td>GPT</td>
<td>8.0 mm</td>
<td>9.0 mm</td>
</tr>
</tbody>
</table>

(Steigenberger et al., 2009)
High-frequency ERP model

DUT1: VieVS minus IERS Conventions

[Graph showing various tidal components and their magnitudes, labeled with different tidal modes like O1, P1, S1, K1, M2, S2K2, Q1, N2, and Sigrid Böhm noted as the author.]
Height changes: GPT vs. ECMWF

Bias

mm

Standard deviation

mm

(Fund et al., 2011)
Ray-tracing Comparison Campaign

Slant factors at 5° elevation

Wettzell

Tsukuba

(Nafisi et al., 2011)
... different weather models

**Slant delays at 5° elevation**

- Eikonal- ECMWF
- Thayer-ECMWF
- Eikonal-JMA
- Thayer-JMA

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Tsukuba

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Wettzell
Geophysical influences on UT1

modified from ftp://gemini.gsfc.nasa.gov/pub/core/fig1.ps

[Michael Schindelegger]
Ray-tracing for VLBI intensive sessions

Intensive sessions INT2
- Saturdays and Sundays
- 1 hour
- Wettzell and Tsukuba
- UT1 determination

1 mm East-Gradient
- 10 cm @ 5° Elevation
- moves station by 7 mm westwards, or
- increases UT1 by 15μs
Ray-tracing for VLBI intensive sessions

VieVS analysis

- KARAT delays for Tsukuba
- improved UT1 (w.r.t. GPS LOD): 23.7 $\rightarrow$ 22.8 $\mu$s
- further improvement by estimating east gradients at Tsukuba

Length of day in ms

[Böhm et al., 2010]
Gravity field

• Atmospheric gravity field corrections of importance for satellite orbits (SLR, GRACE or GOCE).

• **Vertical integration** more accurate than surface pressure approach.

• **Reference** field (pressure) should agree across analysts and with reference pressure for loading.
VLBI analysis: observation level – a posteriori

Average over 50 days

Height Wettzell in mm

[Böhm et al., 2009]
VLBI analysis: observation level – a posteriori

- NNR/NNT accounts for un-modelled loading corrections.

[Böhm et al., 2009]
Atmosphere loading: influence on scale

- Annual amplitude 0.6 mm

[Böhm et al., 2009]
Atmospheric loading

• **Reference pressure** is critical for the TRF.
• Loading corrections **improve repeatability** of baseline lengths.
• **A posteriori corrections** in VLBI analysis are too late (stacking level ist ok).
• Influence on **annual scale variations**.