On the Multi-Technique Combination with Atmospheric Ties

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Motivation

- Regardless of space geodetic observing system (GNSS, VLBI, SLR, and DORIS) estimates of plate tectonics, satellite orbits, Earth’s rotation, and atmospheric state should –in principle- differ only within measurement error bounds, e.g., Krügel et al. (2007), Thaller et al. (2007), Thaller (2008), Nilsson et al. (2015)

- Multi-technique combination facilitates distinction of genuine geophysical signals from technique-specific artefacts, e.g., Rothacher (2002)

- Improvements in ground co-location (more sites with more systems)

In this presentation

- Atmospheric ties from a modeller’s perspective
- Atmospheric ties from a geodesist’s perspective
Chapter 0
Ray-Tracing
How Are the Atmospheric Delays Calculated?

- In-house GFZ’s **ray-tracing software**: Direct Numerical Simulation (DNS) Tool by Zus et al., 2012; 2014

- Input:
  - Refractivity fields: **ERA5** + **IRI2016** (Bilitza, 2018) + **IGRF12** (Thébault et al., 2015)

  - pressure
  - temperature
  - specific humidity
  - geopotential
  - etc.

  - electron density

  - Earth’s magnetic field
Chapter I
Definition of Atmospheric Ties
What Are Atmospheric Ties?

- Expected differences between atmospheric parameters at co-locations obtained independently of space geodetic methods.
- Useful for intra- and inter-technique combination (e.g., Krügel et al., 2007; Thaller, 2008).
- Systematic discrepancies due to:
  - frequency difference (microwave, optical);
  - position difference (mainly height); and
  - observing system differences (technique, geometry, hardware).

- IAG JWG Tropospheric Ties (Heinkelmann et al., 2016) . . . continued for a second term by Kyriakos Balidakis & Daniela Thaller.
Chapter II
Frequency-Induced Differences
Zenith Hydrostatic Delays

- SLR@532nm 6% larger than VLBI/GNSS/DORIS
Zenith Non-Hydrostatic Delays

- SLR@532nm 66 times smaller than VLBI/GNSS/DORIS

$d_{nh}(R/L)$ [1]
Asymmetric Delays I

- Linear gradient components
  - microwave (L-Band)
  - optical (532 nm)

- Spatio-temporally noisy for microwave, smooth for optical

1mm gradient ≈ 3cm@10 degrees
Asymmetric Delays II

- 40-year average asymmetric delay amplitude
  - microwave (L-Band)
  - optical (532 nm)

\[ G = \sqrt{G_{NS}^2 + G_{EW}^2} \]

- Hourly gradient estimates from ERA5 at Wettzell during CONT17

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Balidakis et al. On the Multi-Technique Combination with Atmospheric Ties
Ray-Bending due to Ionospheric Refraction

Based on ERA5, IRI2016, IGRF2014, \( \varepsilon = 3^\circ, \alpha = 0^\circ \)

\[
\int (1 + 10^{-6}N) \, ds_i - \int (1 + 10^{-6}N) \, ds_\infty
\]

\( N \): refractivity, \( ds_i \): ray-trajectory’s element, \( ds_\infty \): ray-trajectory’s element no ionosphere

Note the different colour scales!
Chapter III
Position-Induced Differences
Height-Related Differences

- 100 m height difference (Galileo)

- Zenith hydrostatic delay
  - 27 mm on average

- Zenith non-hydrostatic delay
  - 3 mm on average

- Symmetric/asymmetric delay decreases upwards

- Gradient amplitude

\[ G = \sqrt{G_{NS}^2 + G_{EW}^2} \]

- 0.06 mm on average
  or -3 mm@7°
Spatial Correlation

Microwave gradients decorrelate very fast → difficult to predict

Yarragadee, Australia
Chapter IV
Observing System-Induced Differences
Ray-Bending due to Varying Orbital Altitude

Mapping factor magnitude ranking

\[ m_{fL} < m_{fR}^{h,nh} < m_{fP}^{h,nh} < m_{fD}^{h,nh} \]

L: SLR, R: VLBI, P: GNSS, D: DORIS

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expected \( \delta H \approx 0.2 \text{ mm} \)

expected \( \delta H \approx 2 \text{ mm} \)
Chapter V
Simulation of Space Geodetic Observations
Space Geodetic Adjustment

- Assumption: everything perfectly understood except for non-tidal station motion, atmospheric refraction, and frequency standards’ stability
- Weighted least-squares, statistical tests for outliers, loose relative constrains, absolute constrains, etc.

\[ o - c = m_{fnh}d_{nh}^z + m_g[G_{NS}\cos(\alpha) + G_{EW}\sin(\alpha)] + clk + \delta \hat{x} \]

estimated parameters
\( o \): observed, \( c \): computed, \( m_{fnh} \): non-hydrostatic mapping factor, \( m_g \): gradient mapping factor, \( \epsilon \): elevation, \( \alpha \): azimuth

- NEQs for combination
Chapter VI
Multi-Technique Combination
Introducing Local + Atmospheric Ties

- Imp. for coordinates/troposphere $\rightarrow$ offset/scatter reduction

47% and 66% reduction in zenith delay and gradient scatter resp.
... Introducing 1cm Bias in VLBI Height

- Detr. for coordinates/troposphere $\rightarrow$ offset increase

### Coordinates@VLBI

<table>
<thead>
<tr>
<th>Offset [mm]</th>
<th>R</th>
<th>E</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>single</td>
<td>6</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>LT</td>
<td>8</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>AT</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>LT+AT</td>
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<td>1</td>
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</tr>
</tbody>
</table>

### Atmosphere@VLBI

<table>
<thead>
<tr>
<th>Offset [mm]</th>
<th>$d_{nh}^z$</th>
<th>$10xG_{EW}$</th>
<th>$10xG_{NS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>single</td>
<td>8</td>
<td>6</td>
<td>8</td>
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<tr>
<td>LT</td>
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<tr>
<td>AT</td>
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</tr>
<tr>
<td>LT+AT</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Introducing 1 cm Bias in VLBI $d_{nh}^z$

- Detr. for coordinates/troposphere $\rightarrow$ offset increase
Recapitulation

- Frequency: optical gradients smoother spatially and temporally than microwave
- Position: symmetric/asymmetric delays decrease with increasing altitude
- System: \( mf^L < mf^R_{h,nh} < mf^P_{h,nh} < mf^D_{h,nh} \)
- Based on simulations (PRLD combination with atmospheric and local ties):
  - ATs improve coordinate and troposphere estimation
  - ATs slightly mitigate the “damage” induced by biased LTs
  - ATs useful to detect biased LTs
Thank you!

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Some references


