Explaining the VLBI Estimated Degree-1 Load Variation Via Atmospheric, Oceanic, and Hydrological Mass Variations

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Overview

1. Hydrology Loading
2. Terrestrial Reference Frame Scale
3. Nontidal Ocean Loading
4. Loading Services at GSFC
5. Estimation of Degree-1 Deformation
Hydrology loading series calculation

- NASA GLDAS hydrology model (Rodell et al. 2004)
- Contributions from soil moisture, snow water, plant canopy surface water storage
- Used the 1°x1° monthly average model (1979-present)
- Site displacement loading computed by usual Green’s function approach
- Vertical displacements are 3-10 mm; large annual signal
Hydrology Loading

- Computed annual vertical amplitude of GLDAS loading signal
- Amplitudes from 0 to 10 mm (Amazon basin)
- Annual amplitudes for VLBI sites < 4.5 mm
Hydrology Loading

- VLBI sites: HartRAO (South Africa) and Wettzell (Germany)
- Reasonable agreement of 10-day GRACE mascon loading and GLDAS loading
Comparison of monthly average vertical VLBI position time series at Wettzell and the GLDAS and GRACE mascon loading series.

Correlations between loading series and the VLBI series are 0.57(GLDAS) and 0.48(GRACE)
Hydrology Loading

- Analysis of VLBI operational weekly R1 and R4 network sessions 2003-2010
- Vertical variance is reduced with either the GLDAS or GRACE loading series
## Reference Frame Scale

<table>
<thead>
<tr>
<th></th>
<th>Annual (ppb)</th>
<th>Semi-annual (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cos</td>
<td>sin</td>
</tr>
<tr>
<td>Base case</td>
<td>-0.38</td>
<td>-0.37</td>
</tr>
<tr>
<td>+VMF1+Thermal Def</td>
<td>-0.16</td>
<td>-0.31</td>
</tr>
<tr>
<td>+Atmospheric Load</td>
<td>-0.19</td>
<td>-0.33</td>
</tr>
<tr>
<td>+Hydrologic Load</td>
<td>-0.06</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

Uncertainties = 0.02 ppb

- For the base case, the NMF mapping function was used and no pressure loading was applied
- The biggest reduction in annual amplitude is from hydrology loading
Nontidal Ocean Loading

Nontidal Ocean Loading Calculation

• JPL ECCO ocean model

• Used 12-hour ocean bottom pressure since 1993

• Oceanic volume (not mass) conserving

• Site displacement loading computed by usual Green’s function approach

• Vertical displacements are largest near the coast; large annual signal; rms variation VLBI sites: 0.11-1.67 mm
Nontidal Ocean Loading

RMS variation of the 12h OBP in the ECCO model, 1993-2009
Nontidal Ocean Loading

- Typical vertical loading series at VLBI sites:
  Coastal sites: Matera (Italy) rms 1.18 mm, Onsala (Sweden) rms 0.85 mm, Tsukuba (Japan) rms 0.89 mm
  Inland site: Wettzell (Germany) rms 0.31 mm
- RMS variation is much smaller than VLBI residual vertical RMS
Nontidal Ocean Loading

ECCO Model 1993-2009

Vertical Reduction of w rms (mm)
Nontidal Ocean Loading

ECCO 2000-2010

Length variance reduction (mm²)

Baseline length (1000 km)
Nontidal Ocean Loading

R1+R4 operational networks

Vertical Annual Amplitude (mm)

- Hydrology Loading
- Hydrology+Nontidal Ocean Loading

2000-2009

Station Names:
- ALGOPARK
- BADARY
- FORTLEZA
- GILCREEK
- HARTRAIO
- HOBART76
- KOKKE
- MATERA
- MEDICINA
- NVALE520
- ONSAL60
- SESHAN52
- SVETLOE
- TICOCONC
- TSUKUB32
- WESTFORD
- WETZELL
- ZELENCHEK
Loading Services at GSFC

Hydrology Loading
• GLDAS NOAH model since 1979, updated when data is available
• Monthly series for 170 VLBI stations
• 1x1 degree gridded map with loading series for each lattice point
• http://lacerta.gsfc.nasa.gov/hydlo/

Nontidal Ocean Loading
• JPL ECCO model since 1993, updated when data is available
• 12-hour resolution series for 170 VLBI stations
• 1x1 degree gridded map will be generated in future
• http://lacerta.gsfc.nasa.gov/oclo/

Atmospheric Pressure Loading
• Maintain Petrov-Boy series
• NCEP Reanalysis since 1979, updated when data is available
• 6-hour series for 824 VLBI+GPS+SLR sites
• 2.5x2.5 degree gridded map with loading series for each lattice point
• http://lacerta.gsfc.nasa.gov/aplo_eph/
Blewitt et al. (2001), Trupin et al. (1992): Surface mass load transport =>
1) Displacement of the geocenter
2) Deg-1 deformation of the Earth’s surface

Lavallee and Blewitt (2002): Correlation between VLBI baseline length measurements and deg-1 deformation determined from GPS

- VLBI is not directly sensitive to the geocenter since it is not a satellite technique
- Indirectly sensitive via deg-1 deformation

From Lavallee, 2006
Degree-1 Loading

Displacement of CM relative to CE: $\Delta r_{CM} = \frac{M_L}{M_E} \Delta r_L = \frac{m}{M_E}$  
$m \equiv M_L \Delta r_L$

$M_L = $ transported load mass  
$\Delta r_L = $ center of mass of $M_L$ in CE

Load moment vector $m \sim$ deg-1 coefficients of the surface mass density

$$m = \frac{4\pi R^3}{3} (\sigma_{11c}, \sigma_{11s}, \sigma_{10c})$$

Deg-1 displacement in CF (center of figure frame) is

$$\Delta s = G^T \text{diag}[h_{1}', l_{1}', l_{1}' ] G \frac{m}{M_E}$$  
$G$ is topocentric -> geocentric rotation  
$h_{1}', l_{1}'$ are deg-1 Love numbers in CF

Estimate $m$ from VLBI data. Infer geocenter motion $\Delta r_{CM}$. 
## Geocenter Annual Motion

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amp (mm)</td>
<td>Phase (day)</td>
<td>Amp (mm)</td>
</tr>
<tr>
<td>VLBI 1985-2002</td>
<td>4.3±0.8</td>
<td>10±12</td>
<td>5.0±0.8</td>
</tr>
<tr>
<td>VLBI 1985-2010</td>
<td>9±0.6</td>
<td>36±9</td>
<td>5.5±0.6</td>
</tr>
<tr>
<td>SLR 1993-2002 Moore &amp; Wang (2003)</td>
<td>3.5±0.6</td>
<td>26±10</td>
<td>4.3±0.6</td>
</tr>
<tr>
<td>SLR 2002-2010 Cheng et al. (2010)</td>
<td>3.2±0.4</td>
<td>31±5</td>
<td>2.6±0.4</td>
</tr>
</tbody>
</table>

- VLBI estimates subject to aliasing from higher spherical harmonics
- VLBI global coverage is lacking especially in the southern hemisphere
- Remaining unmodeled annual variation in VLBI
Summary

- Annual site displacement amplitudes are reduced with the VMF1 mapping functions + thermal deformation model + loading corrections

- Application of hydrology loading and nontidal ocean loading reduce the residual site position scatter

- Applying the loading corrections + thermal deformation + VMF1 reduces the annual amplitude of the VLBI reference frame scale from 0.54 ppb to 0.08 ppb

- Estimation of the degree-1 components of surface deformation from VLBI data imply geocenter annual amplitudes that are generally too large compared to those determined from SLR

- In future work we will try to limit aliasing of higher degree terms into the VLBI estimates by applying displacements (deg>1) derived from GRACE or geophysical models (ocean, hydrology, atmosphere)