The use of numerical weather models for SLR data analysis

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<th><strong>Past</strong></th>
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<td><strong>A priori state of the atmosphere is not known</strong></td>
<td><strong>A priori state of the atmosphere is known</strong></td>
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<td><strong>Using global 4D models of the atmosphere and ocean</strong></td>
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<td><strong>Atmosphere pressure loading: direct integration</strong></td>
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<td><strong>Land water storage loading: direct integration</strong></td>
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What is the numerical weather model?

Numerical weather models (NWM) reached that level of sophistication that one can deduce the 4D state of the atmosphere.

How does an NWM work:

- we solve differential equat. and predict state of the atmosphere for $\Delta T$;
- we ingest observations;
- we reconcile them during incremental analysis update (IAU) phase.

Observations are assimilated to the model using the 3D-Var scheme.
Model used:

MERRA: Since 1979.01.01 72 lev $\times 0.5^\circ \times 0.67^\circ \times 6^h$  Latency: $40^d$

GEOS FPIT Since 2000.01.01 72 lev $\times 0.5^\circ \times 0.67^\circ \times 3^h$  Latency: $12^h$

Basis: Fermat principle (1662)

- Variational problem $\rightarrow$ differential equations for the trajectory;
- Numerical solution of equations $\rightarrow$ trajectory;
- Integration of refractivity $\rightarrow$ path delay for each station;
- Path delays at a grid $\rightarrow$ expansion over elevation, azimuth, and time;
- Ingestion of the expansion coefficients into a data analysis package (f.e. GEODYN).
Dataset used:

MERRA  1979.01.01 – 2014.09.30,
GEOS FPIT 2000.01.01 – Present,
168 SLR stations
Updated 4 times a day
Latency: 8–24 hours.

Expansion coefficients are for path delays are computed outside of GEODYN.

Does not need in situ atmospheric pressure measurements.
Validation

VLBI data are processed with a priori path delay from GEOS FPIT

Residual path delay in zenith was adjusted. Average statistics:

Error of wet path delay prediction is \( \sim 10\% \)

A priori path delay at 532 nm can be predicted with accuracy 1–2 mm
Mass Loading service — what is new?

- Using higher resolution models
- Improvement in accuracy
- Extension towards land water storage loading, non-tidal ocean loading, tidal ocean loading
- On-demand computation
- Improvement in latency
**Geophysical Models**

**Old models (2002):**

NCEP Reanalysis: $2.5^\circ \times 2.5^\circ \times 6^h$
1979.01.01 – now; Latency: 2.5–3.5$^d$

**New models (2014)**

Atmosphere:

MERRA: $72 \times 0.5^\circ \times 0.67^\circ \times 6^h$
1979.01.01 – now; Latency: 20–60$^d$

GEOS-FP: $72 \times 0.25^\circ \times 0.3125^\circ \times 3^h$
2011.09.01 – now; Latency: 9–16$^h$

GEOS-FPIT: $72 \times 0.5^\circ \times 0.66^\circ \times 3^h$
2000.01.01 – now; Latency: 8–30$^h$

Land water Storage:

MERRA: $0.5^\circ \times 0.67^\circ \times 1^h$

GEOS-FPIT: $0.5^\circ \times 0.67^\circ \times 1^h$

GLDAS NOAH025 $0.25^\circ \times 0.25^\circ \times 3^h$
2000.02.24 – now; Latency: 35–75$^d$

Non-tidal ocean loading:

Ocean water mass conservation condition OMCT: $1.875^\circ \times 1.875^\circ \times 6^h$
2001.01.01 – now; Latency: 30–90$^d$
**Traditional approach (Farrell, 1972):** pressure difference $\Delta P \rightarrow$ applying land-sea mask $L \rightarrow$ convolution integral:

\[
\vec{u}_r(\vec{r}, t) = \int \int_{\Omega} L(\phi', \lambda') \Delta P(\vec{r}', t) G_R(\psi(\vec{r}, \vec{r}')) \cos \phi' \, d\lambda' \, d\phi'
\]

\[
\vec{u}_h(\vec{r}, t) = \int \int_{\Omega} \vec{q}(\vec{r}, \vec{r}') L(\phi, \lambda) \Delta P(\vec{r}', t) G_H(\psi(\vec{r}, \vec{r}')) \cos \phi' \, d\lambda' \, d\phi'
\]

where Green’s functions are defined

\[
G_R(\psi) = \frac{fa}{g_0^2} \sum_{n=0}^{+\infty} h'_n P_n(\cos \psi) \quad G_H(\psi) = -\frac{fa}{g_0^2} \sum_{n=1}^{+\infty} l'_n \frac{\partial P_n(\cos \psi)}{\partial \psi}
\]

Complexity: $O(d^4)$
Spherical harmonics approach: pressure difference $\rightarrow$ upgridding $\rightarrow$ applying land-sea mask $L$ $\rightarrow$ spherical harmonic transform $\rightarrow$ scaling with Love numbers $\rightarrow$ inverse spherical harmonic transform.

\[ V_{nm}^m(t) = \frac{1}{\bar{\rho}_\oplus g_0} \frac{3h'}{2n+1} \int \int_{\Omega} L(\phi, \lambda) \Delta P(t, \phi, \lambda) Y_{n}^m(\phi, \lambda) \cos \phi \, d\phi \, d\lambda \]

\[ H_{nm}^m(t) = \frac{1}{\bar{\rho}_\oplus g_0} \frac{3l'}{2n+1} \int \int_{\Omega} L(\phi, \lambda) \Delta P(t, \phi, \lambda) Y_{n}^m(\phi, \lambda) \cos \phi \, d\phi \, d\lambda \]

\[
\begin{align*}
D_U(\phi, \lambda) &= \sum_{i=0}^{i=m} \sum_{j=-n}^{j=n} V_{ij} Y_{ij}(\phi, \lambda) \\
D_E(\phi, \lambda) &= \sum_{i=0}^{i=m} \sum_{j=-n}^{j=n} H_{ij} \frac{\partial Y_{ij}(\phi, \lambda)}{\partial \lambda} \\
D_N(\phi, \lambda) &= \sum_{i=0}^{i=m} \sum_{j=-n}^{j=n} H_{ij} \frac{\partial Y_{ij}(\phi, \lambda)}{\partial \phi}
\end{align*}
\]

Complexity: $O(d^3)$
Enhancements:

- Up-gridding pressure field to degree 2047 (4.9 km) for ocean loading and degree 1023 (9.8 km) for other loadings.

- Refined land-sea mask GTOPO30 with an original resolution 30″.

- Using 3D atmosphere to compute surface pressure after up-gridding.

- Clean “humidity voids” in the atmosphere pressure field.

- Masking glaciers and big reservoirs in land water storage models.

- “Conditioning” bottom pressure from the OMCT model to alleviate artifacts due to truncation.
• Time series of 3D loading displacements for 849 stations caused by
  – atmosphere 1979.01.01 – now, latency: \(15^h\).
  – land water storage 1979.01.01 – now, latency: \(15^h\).
  – non-tidal ocean 2001.01.01 – now, latency: \(45^d\).

• Time series of the above 3D loading displacements at \(1^\circ \times 1^\circ\) grid.

• Coefficients of loading harmonic variations at 11–20 frequencies for both 849 stations and at \(1^\circ \times 1^\circ\) grid.

• Coefficients of ocean loading displacements for both 849 stations and at \(1^\circ \times 1^\circ\) grid using model GOT4.8 and FES2012.

• Loadings are computed in the CM frame. Loading displacement differences CF – CM are provided as well.

• Loading displacements are updated within 1 hour upon the model update.

In total, over 1,000,000 files, 200 Gb.
Validation

Data: VLBI observations 2001.01.01 – 2014.07.02

Method: estimation of global admittance factors

A priori: toc_fes2012, nto_omct

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<th>GEOS-FPIT</th>
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<td>Atm</td>
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<tr>
<td>GEOS-FPIT UP</td>
<td>0.963 ± 0.023</td>
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<tr>
<td>GEOS-FPIT EA</td>
<td>0.609 ± 0.049</td>
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<tr>
<td>GEOS-FPIT NO</td>
<td>1.027 ± 0.041</td>
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<tr>
<td>Lws</td>
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<tr>
<td>GEOS-FPIT UP</td>
<td>0.955 ± 0.016</td>
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<tr>
<td>GEOS-FPIT EA</td>
<td>0.804 ± 0.029</td>
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<tr>
<td>GEOS-FPIT NO</td>
<td>0.886 ± 0.024</td>
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<tr>
<td>NOAH025</td>
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<tr>
<td>UP</td>
<td>1.220 ± 0.013</td>
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<tr>
<td>EA</td>
<td>0.660 ± 0.030</td>
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<tr>
<td>NO</td>
<td>0.826 ± 0.033</td>
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Contribution to the geopotential

Companion-service of the contribution to the geopotential due to

- atmosphere
- land water storage
- non-tidal ocean
- tidal ocean

Degree/order truncation: 64;
The same geophysical models as for loading;
The same latencies as for loading.

Latency of land water storage contribution to geopotential
International Mass Loading Service
launched in 2014.

• Includes
  – Atmospheric loading
  – Land water storage loading
  – non-tidal ocean loading
  – tidal ocean loading

• Provides the contribution to the geopotential due to fluids

• Provides time series of displacements with 3–6 hours time resolution for
  – ∼1000 space geodesy stations
  – 1° × 1° grid
  – on-demand

• Has latencies 15 hours for atmosphere and land water, 40 days for non-tidal ocean loading.

• Validated against VLBI data

http://massloading.net
Further development:

- Using weather forecast to $0-24^h$ in the future. Latency will be eliminated. Accuracy degradation: 20% for the current instant.

- Using OPeNDAP for distribution of path delays, loading displacements and the contribution to the geopotential

  http://massloading.net/atm/ondemand.asc?dspl&
  dspl.model=auto&
  station(dspl,Annapolis,1130794.763,-4831233.803,3994217.042)&
  station(dspl,MYsta1,1492233.328,-4458089.491,4296046.016)&
  time(dspl,20141015T11:00:00,20141015T18:00:00)

- Automation of loading displacement and slant path ingestion: development of a client library that communicates with the server automatically:

  get_loading ( char* config_file, load_struct *loading_result )
  get_spd ( char* config_file, spd_struct *path_delay )
Summary

• Computation of slant path delay from numerical weather models is ready for *routine* data processing of all SLR observations. Interface to GEODYN is available.

• A priori path delay through the atmosphere is expected to be accurate at 1–2 mm level — 10 times better than using surface pressure.

• Mass loading service that provides both loading displacements and contribution to the geopotential is launched. Results are available on-line for *routine* data processing.

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