The use of numerical weather models for SLR data analysis

Leonid Petrov *ADNET Systems INC, USA*

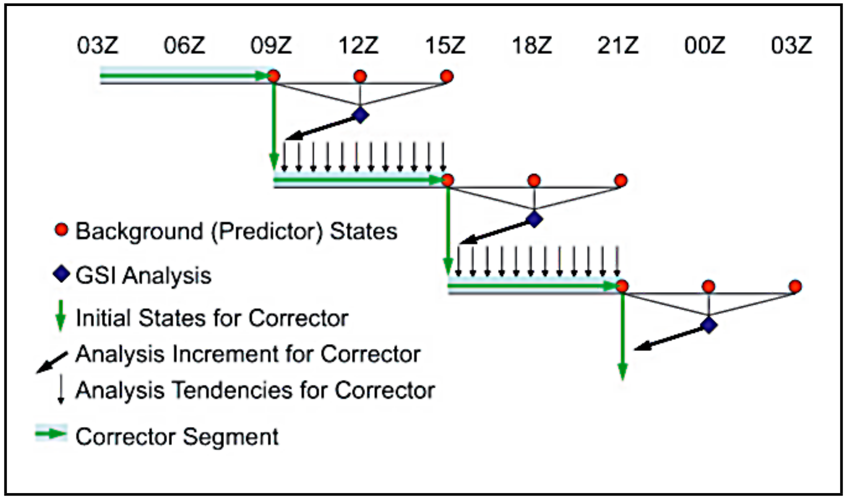
Modeling the atmosphere: paradigm shift

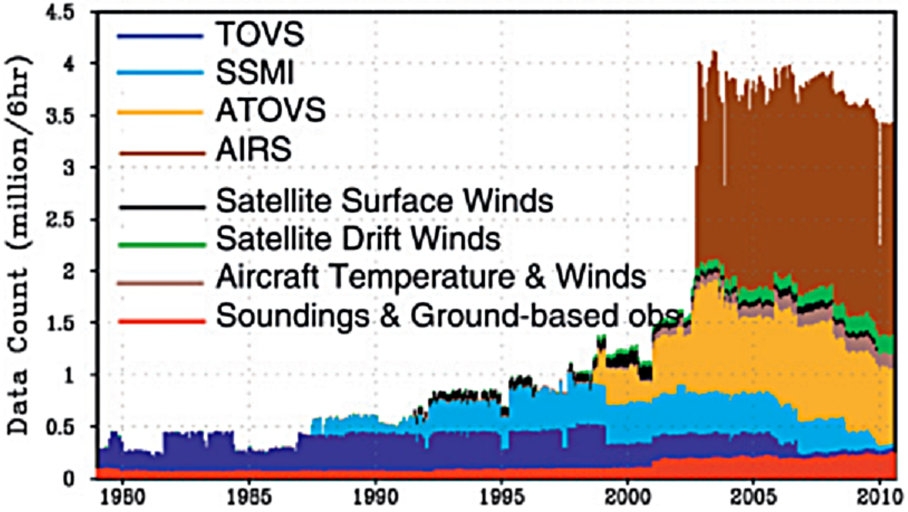
Past	*Present*
A priori state of the atmosphere is **not known**	A priori state of the atmosphere is **known**
In situ **1D** measurements of meteorological parameters	Using **global 4D** models of the atmosphere and ocean
Path delay: Marini-Murray mapping function	Numerical integration of wave propagation equations through the heterogeneous media
Atmosphere pressure loading: regression coefficients	Atmosphere pressure loading: direct integration
Land water storage loading: no model	Land water storage loading: direct integration

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 ΔT;
- we ingest observations;
- we reconcile them during incremental analysis update (IAU) phase.

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

Slant path delay computation

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 ⟶ differential equations for the trajectory;
- Numerical solution of equations ⟶ trajectory;
- Integration of refractivity ⟶ path delay for each station;
- Path delays at a grid ⟶ 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.

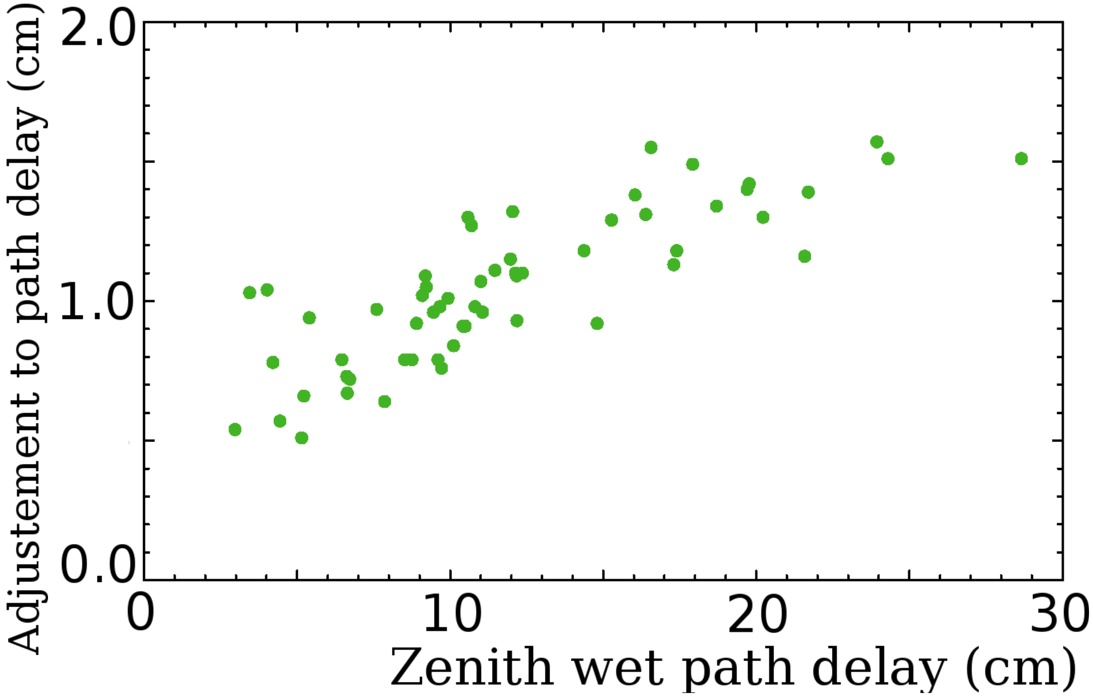
Expansion coefficients are for path delays are computed *outside* of GEODYN.

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):	**New models (2014)**
Atmosphere:	
NCEP Reanalysis: $2.5^\circ \times 2.5^\circ \times 6^h$ 1979.01.01 – now; Latency: 2.5–3.5^d	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:	
none	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

Loading computation

Traditional approach (Farrell, 1972): pressure difference ΔP ⟶ applying land-sea mask L ⟶ convolution integral:

$$\begin{aligned}
\vec{u}_r(\vec{r},t) &= \iint\limits_{\Omega} L(\phi',\lambda')\,\Delta P(\vec{r}\,',t)\,G_{\mathrm{R}}(\psi(\vec{r},\vec{r}'))\cos\phi'\,d\lambda' d\phi' \\
\vec{u}_h(\vec{r},t) &= \iint\limits_{\Omega} \vec{q}(\vec{r},\vec{r}\,')\,L(\phi,\lambda)\,\Delta P(\vec{r}\,',t)\,G_{\mathrm{H}}(\psi(\vec{r},\vec{r}'))\cos\phi'\,d\lambda' d\phi'
\end{aligned}$$

where Green's functions are defined

$$G_{\mathrm{R}}(\psi) = \frac{fa}{g_0^2}\sum_{n=0}^{+\infty} h_n^{'} P_n(\cos\psi) \qquad G_{\mathrm{H}}(\psi) = -\frac{fa}{g_0^2}\sum_{n=1}^{+\infty} l_n^{'} \frac{\partial P_n(\cos\psi)}{\partial\psi}$$

Complexity: $O(d^4)$

Spherical harmonics approach: pressure difference ⟶ upgridding ⟶ applying land-sea mask L ⟶ spherical harmonic transform ⟶ scaling with Love numbers ⟶ inverse spherical harmonic transform.

$$
\begin{aligned}
V_n^m(t) &= \frac{1}{\bar{\rho}_\oplus\, g_0} \frac{3h'}{2n+1} \iint\limits_{\Omega} L(\phi,\lambda)\, \Delta P(t,\phi,\lambda)\, Y_n^m(\phi,\lambda) \cos\phi \, d\phi \, d\lambda \\
H_n^m(t) &= \frac{1}{\bar{\rho}_\oplus\, g_0} \frac{3l'}{2n+1} \iint\limits_{\Omega} L(\phi,\lambda)\, \Delta P(t,\phi,\lambda)\, Y_n^m(\phi,\lambda) \cos\phi \, d\phi \, d\lambda
\end{aligned}
,
$$

$$
\begin{aligned}
D_U(\phi,\lambda) &= \sum_{i=0}^{i=m} \sum_{j=-n}^{j=n} V_j^i \, Y_j^i(\phi,\lambda) \\
D_E(\phi,\lambda) &= \sum_{i=0}^{i=m} \sum_{j=-n}^{j=n} H_j^i \, \frac{\partial Y_j^i(\phi,\lambda)}{\partial \lambda} \\
D_N(\phi,\lambda) &= \sum_{i=0}^{i=m} \sum_{j=-n}^{j=n} H_j^i \, \frac{\partial Y_j^i(\phi,\lambda)}{\partial \phi}
\end{aligned}
.
$$

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.

Results

- 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

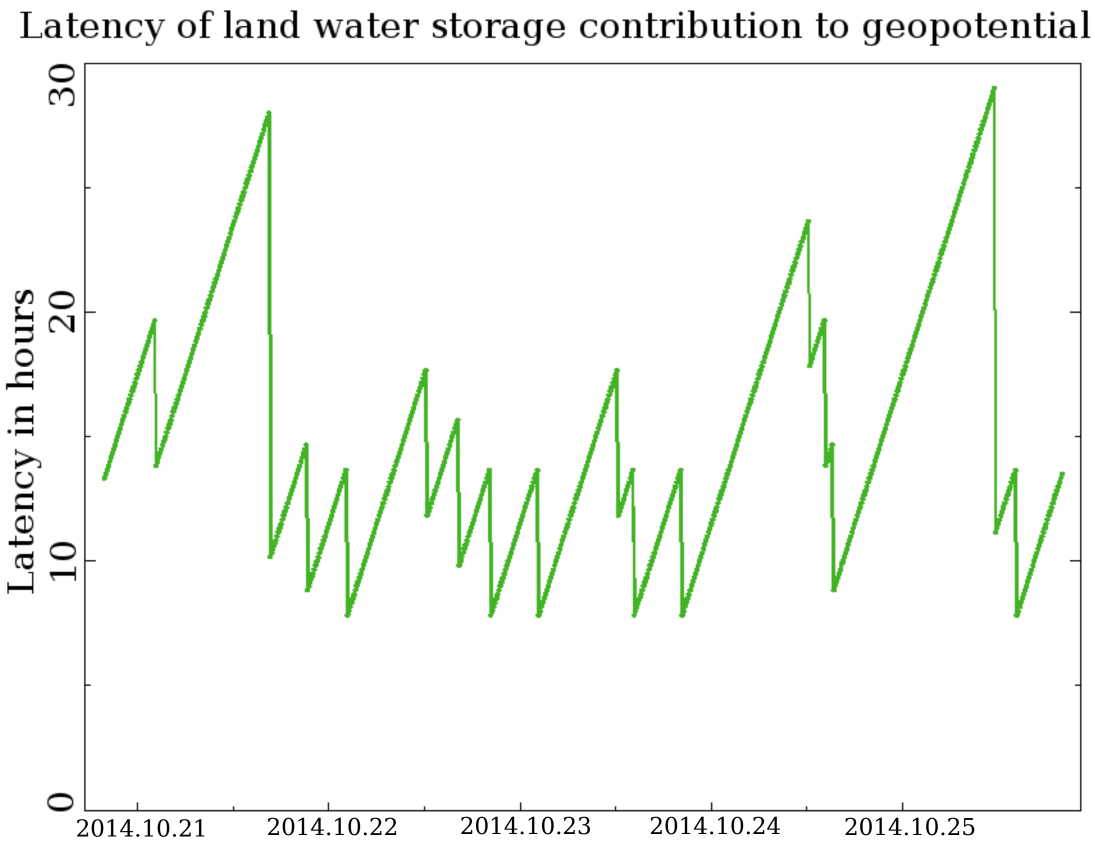
A priori: toc_fes2012, nto_omct

Atm GEOS-FPIT UP	0.963	±	0.023
Atm GEOS-FPIT EA	0.609	±	0.049
Atm GEOS-FPIT NO	1.027	±	0.041
Lws GEOS-FPIT UP	0.955	±	0.016
Lws GEOS-FPIT EA	0.804	±	0.029
Lws GEOS-FPIT NO	0.886	±	0.024
Lws NOAH025 UP	1.220	±	0.013
Lws NOAH025 EA	0.660	±	0.030
Lws NOAH025 NO	0.826	±	0.033

Contribution to the geopotential

Companion-service of the contribution to the geopotential due to

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


Latency of land water storage contribution to geopotential

Degree/order truncation: 64;

The same geophysical models as for loading;

The same latencies as for loading.

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^h time resolution for
  - ~ 1000 space geodesy stations
  - $1^\circ \times 1^\circ$ 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

What is next?

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.

This project was supported by NASA Earth Surface and Interior program.