ASSESSING THE IMPACT OF NON-TIDAL ATMOSPHERIC LOADING ON A KALMAN FILTER-BASED TERRESTRIAL REFERENCE FRAME

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1. MOTIVATION

- To contribute to the analysis of the IERS campaign on the effects of the Non Tidal Atmospheric Loading (NTAL) in space-geodetic (SG) data processing.
- **A-posteriori removal** of NTAL displacements from time series of SG positions obtained with GPS, VLBI, SLR and DORIS.
- Evaluation of the **impact of the removal** on global frame parameters: ***(i)* geocentre motion, *(ii)*** on the **datum parameters** and ***(iii)*** on the **velocity fields** of secular terrestrial reference frames (**TRFs**).
- **Consistency** between the NTAL models and SG solutions is examined: How do differences in SG-derived velocities and geocentre motion compare with those inferred from the NTAL models?
- Is it possible to apply a **Remove/Restore** approach without corrupting the secular TRFs?

2. DATA SETS

1. **SG SINEX** files of GPS, VLBI, SLR and DORIS (station positions and Earth Orientation parameters):

Table 1. *Time span, temporal resolution and number of SINEX files provided by the analysis centres (AC) for each of the 4 SG solutions.*

SG Technique	Data Span	AC	Temporal Resolution	# SNX
VLBI	2006 - 2011	GSFC	Daily (Session-wise)	961
GPS	2006 - 2011	CODE	Daily	2191
SLR	2006 - 2011	GFZ	Weekly	312
DORIS	2006 - 2011	GSFC	Weekly	260

2. **NTAL models** Time series of station displacements at the ITRF sites (6 h time lag). The models are based on NCEP surface pressure data and the station displacements are expressed in the Center of Mass (**CM**) frame.

3. DATA EDITING

- Why is data cleaning important?
  To avoid that stations characterized by few observations may perturb the velocity estimates when removing NTAL.
- Stations (i) with *less than 3 years* of observations, (ii) characterised by position breaks, (iii) with less than 150 observations (for VLBI) have been removed from the SINEX files.

4. NTAL REMOVAL (Figure 1)

- Daily/Weekly mean load displacementes (ITS, *in Fig 1*) have been removed from the CM-centered SINEX files.
- As a result of the removal procedure, we obtain:

1. *Corrected (CORR, in Fig 1) SINEX files* free from atmospheric loading signals have been obtained.
2. *Simulated (SIM, in Fig 1) SINEX files* containing the integrated loading models at the ITRF sites for each SG techniques along with the covariance matrix of the station positions

5. GEOCENTRE MOTION

- Translational time series derived from SLR with (CM SINEX, cf Fig 1) and without NTAL models (CORR SINEX, cf Fig 1) have been compared.

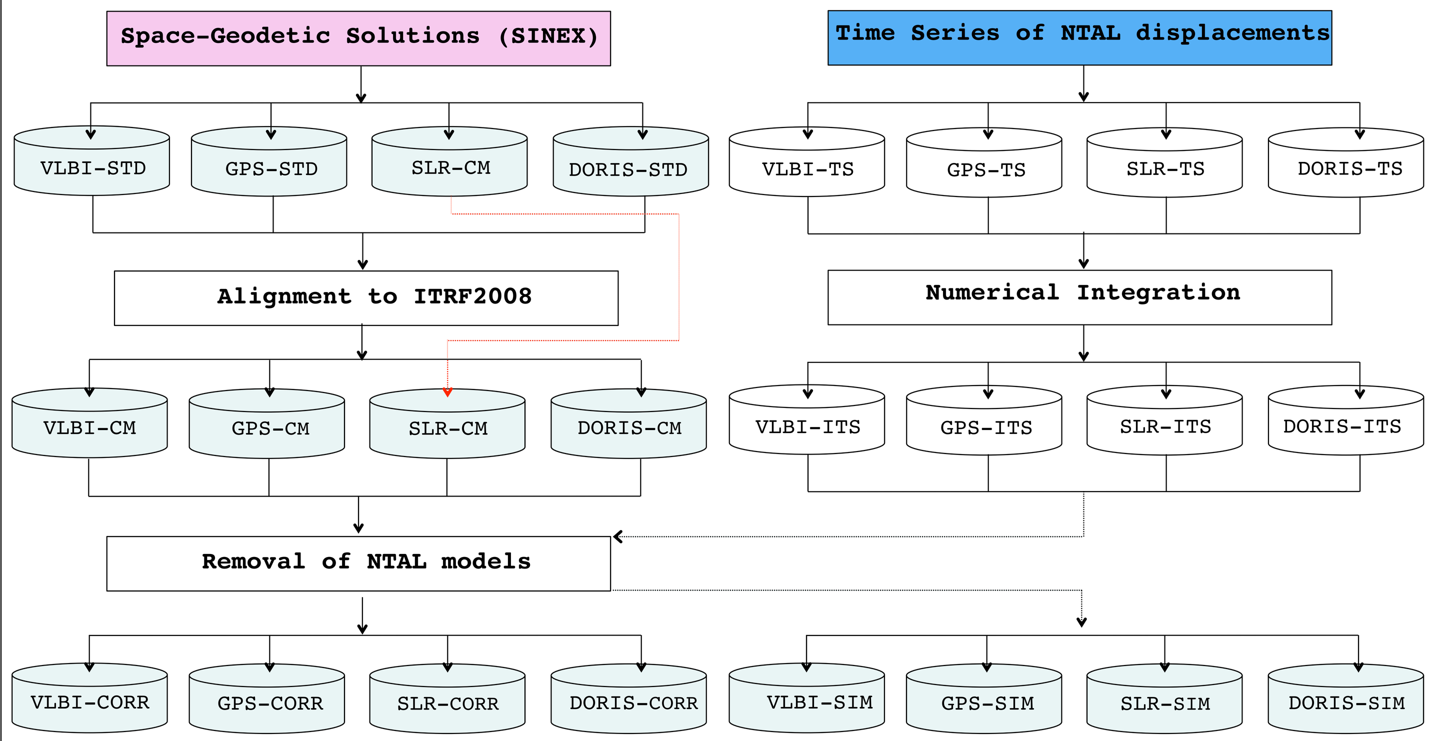

Figure 1. *Steps involved in the removal of NTAL models (left side of the chart) from the SG solutions (right side). STD: standard SINEX, CM: Center of Mass centered SINEX, CORR: corrected SINEX, ITS: integrated NTAL time series, SIM: simulated NTAL SINEX*

5. GEOCENTRE MOTION - Cont'd

- Table **2** reports the estimates of the seasonal components for the 2 translational time series.

Table 2. *Annual and Semi-annual components of the SLR geocentre time series obtained by stacking the CM and CORR SINEX files (cf Fig 1). Phases and amplitudes have been computed according to* $A\sin[\omega(t-t_0)-\varphi]$ *, where* ω *is the annual/semi-annual frequency,* φ *phase and t is expressed in decimal years. Formal errors are parenthesized.*

SLR		Annual		Semi-annual	
		A [mm]	φ [deg]	A [mm]	φ [deg]
Tx	CM	2.7 (0.3)	132.48 (4.67)	1.1 (0.3)	342.04 (15.04)
	CORR	2.6 (0.3)	140.27 (4.42)	1.1 (0.3)	332.28 (12.58)
Ty	CM	1.8 (0.3)	40.03 (7.16)	0.8 (0.3)	299.08 (10.87)
	CORR	1.4 (0.3)	13.38 (9.78)	0.4 (0.2)	290.42 (11.20)
Tz	CM	8.8 (0.5)	105.95 (3.25)	1.1 (0.5)	333.41 (24.57)
	CORR	6.1 (0.5)	115.05 (4.26)	0.9 (0.5)	330.52 (27.84)

- Only the T_Z annual component proves significantly affected. The amplitude difference induced by the NTAL corrections is **2.7 mm.**
- SIM SINEX files (cf Fig 1) containing the NTAL atmospheric displacements at SLR sites have been stacked adopting full covariance matrices and solving for weekly translation parameters. These quantify the geocentre motion implicitly contained in the loading models in addition to the aliased load effect.

Table 3. *Annual and Semi-annual components of the geocentre motion induced by the atmospheric displacements at the SLR sites.*

NTAL		Annual		Semi-annual	
		A [mm]	φ [deg]	A [mm]	φ [deg]
Tx	SIM	0.7 (0.1)	86.71 (3.40)	0.2 (0.1)	82.99 (3.93)
Ty	SIM	1.0 (0.1)	84.06 (2.36)	0.4 (0.1)	321.95 (5.49)
Tz	SIM	3.1 (0.1)	88.00 (2.08)	0.3 (0.1)	340.17 (16.41)

The annual signal amplitude of the T_Z component is **3.1 mm** and proves to be in good agreement with the decrease of **2.7 mm** caused by the NTAL corrections.

6. KALMAN FILTER-BASED COMBINATION

CM and CORR SINEX files have been combined. Linear frames have been estimated (no seasonal component, no process noise).
The Helmert parameters (offsets and rates) between the 2 frames with and without NTAL models are reported in Table 4.

Table 4. *Parameter offsets and rates between the combined reference frames estimated with and without NTAL displacements. Rotations (not reported) are zero. Reference epoch for the parameter is 2005:001. Formal errors are parenthesized. Values are in* mm *and* mm/yr

	Tx	Ty	Tz	D
offset	0.08 (0.10)	0.20 (0.10)	0.29 (0.27)	0.03 (0.09)
rate	0.00 (0.02)	-0.04 (0.02)	-0.05 (0.06)	-0.03 (0.02)

The parameters are not statistically different from zero (with the exception of T_y and its rate), thus showing the removal of the NTAL displacements does not significantly affect the secular reference frames.

7. VELOCITY FIELDS

Single-technique velocity fields related to CM and CORR SINEX files have been estimated and differences $dv=v_{CM}-v_{CORR}$ between the 2 velocity fields have been determined and plotted in Figure 2 as a function of the number of observations (in days).
The horizontal components of the velocities prove less affected by the NTAL corrections. The scatter of the velocity differences increases for the Height component.
The velocity differences are well within the range [-0.5,+0.5] mm/yr.

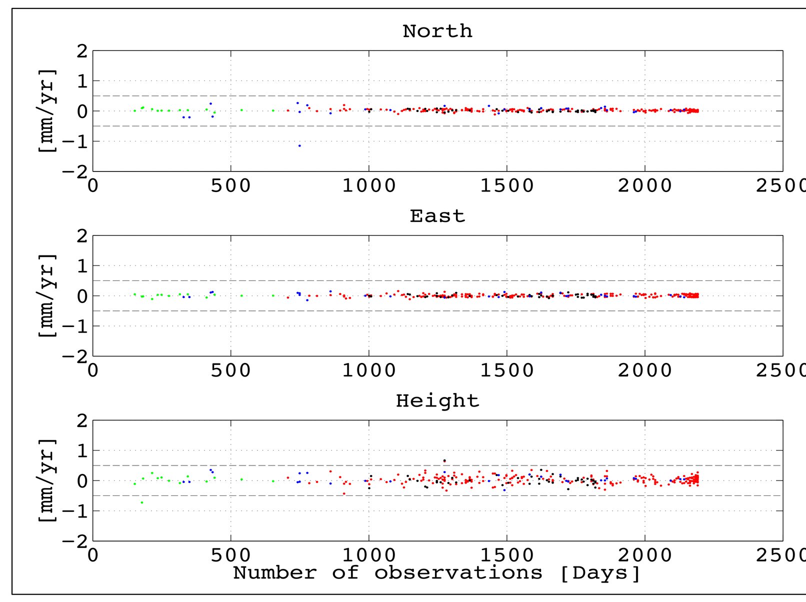

Figure 2. Differences btw the 2 derived velocity fields obtained by stacking the CM and the CORR SINEX files are plotted as a function of the number of observations. The black dotted lines mark the range [-0.5, 0.5] mm/yr.
Red dots: GPS
Blue dots: SLR
Green dots: VLBI
Black dots: DORIS

8. CONSISTENCY between VELOCITY FIELDS

Is it possible to infer the impact of the NTAL corrections on the velocity from the integrated NTAL time series at the ITRF sites?
3 approaches have been tested (see Figure 3):

- (AL-F) Stack of the atmospheric SIM SINEX files with full covariance
- (AL-Id) Stack of the SIM SINEX with an identity matrix
- (AL-LR) Linear Regressions (with an identity matrix)of the NTAL integrated time series computed per site.

Figure 3 shows perfect linear correlation btw the 2 velocity fields is achieved when the NTAL displacements are stacked adopting full covariance matrices.

Simple linear regressions of the atmospheric models computed per site do not agree with the velocity differences determined from SG observations.

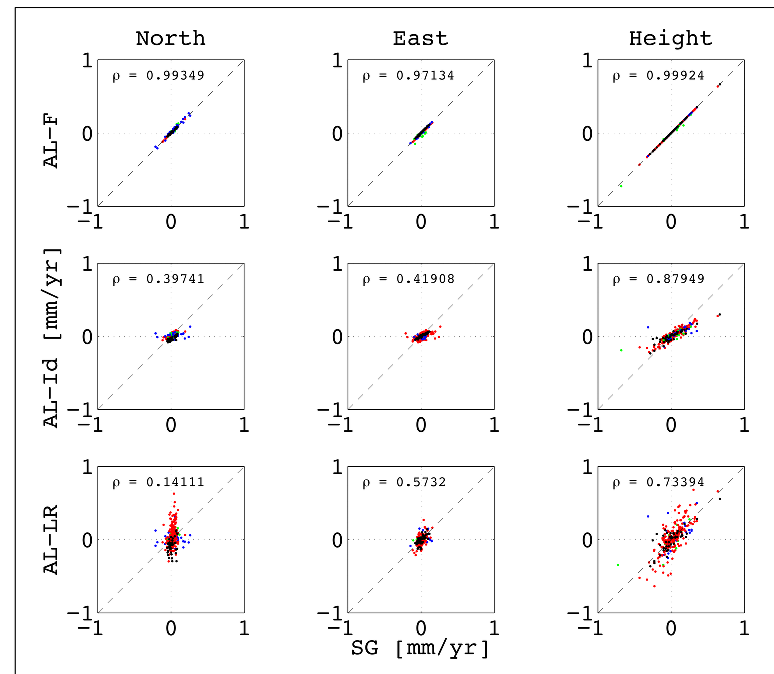

Figure 3. Comparison btw the velocities estimated from the integrated NTAL time series (ordinates) and the velocity differences of the SG solutions due to the removal of the NTAL models (abscissae).
Estimation of the atmospheric linear trends:
- **AL-F:** stacks of the atmospheric SINEX file with full covariance matrix
- **AL-Id:** stacks with identity matrix
- **AL-LR:** linear regressions of integrated NTAL time series

Red GPS Blue SLR Green VLBI Black DORIS

9. REMOVE/RESTORE

Offsets (*mm*) and rates (*mm/yr*) between the 2 GPS-only frames obtained stacking CM and CORR SINEX files have been estimated: (Formal error not scaled by the reduced chi-square are parenthesized. Reference epoch 2005:001)

	T_x	T_y	T_z	D	R_x	R_y	R_z
offset	-0.03 (0.44)	-0.28 (0.45)	0.11 (0.58)	0.04 (0.46)	-0.06 (2.16)	0.02 (2.15)	0.01 (2.14)
rate	-0.04 (0.10)	0.08 (0.10)	-0.08 (0.13)	-0.02 (0.11)	0.02 (0.54)	0.01 (0.54)	-0.01 (0.54)

If we restore the removed NTAL displacements adopting the full covariance matrices (AL-F, see Fig 3)

	T_x	T_y	T_z	D	R_x	R_y	R_z
offset	0.00 (0.44)	0.00 (0.45)	0.00 (0.58)	0.00 (0.46)	0.00 (2.16)	0.00 (2.15)	0.00 (2.14)
rate	0.00 (0.10)	0.00 (0.10)	0.00 (0.13)	0.00 (0.11)	0.00 (0.54)	0.00 (0.54)	0.00 (0.54)

If we adopt instead the identity matrix (AL-Id, see Fig 3), the frame offsets and rates differ from zero (with maximum difference up to 0.11 mm (T_y) and 0.03 mm/yr ($\dot{T}_y$))

CONCLUSIONS

If stations with less than 3 years of observations are removed

- the reduction observed in the amplitude of the annual component of the Tz component of geocentre motion is consistent with the one related to the NTAL models
- the datum parameters of the secular reference frames are not affected
- the NTAL corrections do not affect the velocities more than (+/-) 0.5 mm/y
- the impact of the loading corrections on the velocities can be inferred from the integrated NTAL time series only if we stack the loading displacements with full covariance matrices of the station positions (approach AL-F, see Fig 3).
- The Remove/Restore procedure is sensitive to the way linear regressions of the NTAL models are computed. Perfect consistency between the restored and the original secular frames is achieved by adopting strategy AL-F (See Fig 3)

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