How DORIS observations can independently contribute to the realization of the ITRF origin

A. Couhert[1,*], F. Mercier[1], J. Moyard[1], R. Biancale[1,2]

[1] Centre National d'Etudes Spatiales, Toulouse, France
[2] Deutsche GeoForschungsZentrum, Oberpfaffenhofen, Germany

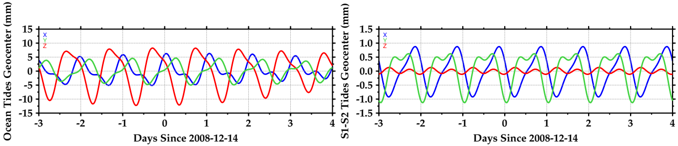
*Mail : alexandre.couhert@cnes.fr

IDS AWG
Toulouse, France
June 11, 2018

DEFINITIONS

- Motion of the *center-of-mass* (CM) of the whole Earth w.r.t. the *center-of-figure* (CF) of the solid Earth's surface (Ray 1999)
  - *Tidal* geocenter (models available from the IERS Conventions 2010)

Geophysical Cause	Size	IERS Conventions
Oceans	sub-mm to a few mm	OK
Atmosphere	~ 1 mm	OK



Ocean (left) and S1/S2 atmospheric (right) tide geocenter coordinates

  - *Non-tidal* component of the geocenter motion

Geophysical Cause	Size	IERS Conventions
GIA	~ 1 mm/y	OK (in ITRF coordinates)
Continental water	several mm	X
Thermoelastic effects	~ 1 mm ?	X

ITRF ORIGIN

- The *ITRS* origin should be the instantaneous CM
  - Satellite geodetic techniques sense geocenter motion as satellites dynamical motion defines CM (according to Newton's laws) while ground station networks are located on the solid Earth surface
- In practice, the IERS Conventions 2010 substitute the *ITRF* origin for CF or a long-term average of CM realizations

$$\vec{X} = \vec{X}_{ITRF} - \vec{O}_G, \tag{4.16}$$

where $\vec{O}_G$ represents the geocenter motion in ITRF (vector from the ITRF origin to the instantaneous center of mass) <[2]>.

  - Geodetic networks coverage of the Earth surface is limited $\Rightarrow$ CF remains a purely theoretical concept and only their *center-of-network* (CN) is accessible
- Currently, SLR observations of the LAGEOS-1 and 2 satellites solely contribute to the realization of the ITRF origin

CONTEXT

- **Motivation**
  - Geocenter motion is the largest limiting factor when comparing orbits based on different tracking techniques (Couhert et al. 2015)
    - Affecting *MSL* observations of satellite altimetry & GRACE mass estimates

Error Source	Time Scale	Global	Regional	Rationale
Tracking Data Residual Consistency	seasonal		3–8 mm	SLR v. GPS/DORIS orbits
	interannual		3 mm/y	
	decadal		2 mm/y	
Reference Frame	seasonal		8 mm	GPS v. SLR+DORIS, ITRF08 v. 05
	interannual	0.03 mm/y	1 mm/y	
	decadal	0.05 mm/y	0.3 mm/y	
Time Variable Gravity	seasonal		4 mm	Mean field v. 10-day series and external orbits
	interannual	0.1 mm	2 mm/y	
	decadal	0.1 mm/y	1.5 mm/y	

Radial orbit error budget for the Jason series POE-D solutions

- **DORIS status**
  - The geocenter vector measured by DORIS so far ended with a lesser precision (Willis et al. 2006 ; Altamimi et al. 2016), given the less accurate positioning information, and the challenges to precise orbit determination presented by the satellites tracked

QUESTIONS RAISED

- Which processes are responsible for the corruption of the current IDS DORIS-based geocenter estimates ?
- Has DORIS the sensitivity to monitor geocenter motion ?
- How providing reliable independently derived geocenter coordinates to contribute to the Earth’s center of mass determination ?

COLLINEARITY ISSUES MITIGATION

- *Zenith Tropospheric Delay* parameters are correlated with station height modeling errors (inaccuracy not accounted for)
  - Station heights $\Delta r^{\text{CF}}_{i,\text{load}_{\text{non-tidal}}}$ should be estimated simultaneously with the geocenter translation $\vec{O}_{\text{G}_{\text{non-tidal}}}$

$$\vec{X}^{\text{CM}}_i(t) \simeq \vec{X}^{\text{CN}}_{i,\text{ITRF}}(t_0)+(t-t_0)\dot{\vec{X}}_{i,\text{ITRF}}+\Delta\vec{c}^{\,\text{CM}}_{i,\text{load}_{\text{tidal}}}(t)+\Delta r^{\text{CF}}_{i,\text{load}_{\text{non-tidal}}}(t)-\vec{O}_{\text{G}_{\text{non-tidal}}}(t)$$

  - DORIS data should be processed down to as low elevation angles as possible
    - Switching from $10°$ to $5°$ elevation cut-off angle corresponds to an increase in the number of observations by up to $\sim 20\%$
  - A *sensible* elevation-dependent weighting of the observations should be used
    - Based on the DORIS antenna gain and propagation knowledge
  - Horizontal tropospheric gradients should be solved for

Collinearity Issues Mitigation

- *Solar Radiation Pressure* modeling deficiencies primarily affects the Z geocenter (Willis et al. 2006 ; Gobinddass et al. 2009 ; Meindl et al. 2013) derived from the non-spherical satellites
  - Sun-synchronous satellites should be disregarded, because of their draconitic period of ∼365-day
  - An exclusive cross-track observability of the T_Z coordinate should be secured ⇒ *Vertical site displacements should be estimated*

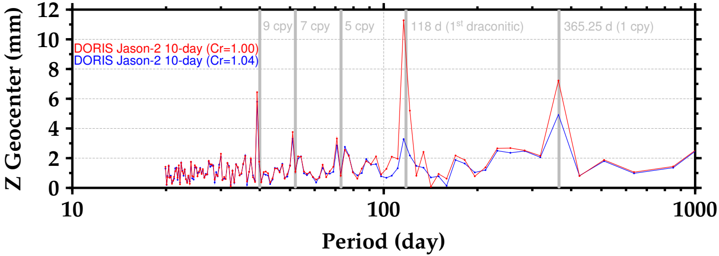
$$
\begin{aligned}
\delta_R(t) &= -\frac{\dot{\delta}_S(0)}{2\omega_0}\cos\omega_0 t + \frac{\dot{\delta}_R(0)}{\omega_0}\sin\omega_0 t \\
\delta_S(t) &= \left(\frac{1}{{\omega_0}^2}\left[\frac{R_{s_0}}{2} - T_Z\frac{GM}{r^3}\sin i\right] + 2\frac{\dot{\delta}_R(0)}{\omega_0}\right)\cos\omega_0 t \\
&\quad + \left(-\frac{R_{c_0}}{2{\omega_0}^2} + \frac{\dot{\delta}_S(0)}{\omega_0}\right)\sin\omega_0 t - 2\frac{\dot{\delta}_R(0)}{\omega_0} + \delta_S(0) \\
\delta_W(t) &= \delta_W(0)\cos\omega_0 t + \frac{\dot{\delta}_W(0)}{\omega_0}\sin\omega_0 t + \frac{1}{{\omega_0}^2}\left(C_{N_0} + T_Z\frac{GM}{r^3}\cos i\right)
\end{aligned}
$$

Impact of a geocenter Z-shift (T_Z) perturbation on satellite dynamics

COLLINEARITY ISSUES MITIGATION

- *Solar Radiation Pressure* modeling deficiencies primarily affects the Z geocenter (Willis et al. 2006 ; Gobinddass et al. 2009 ; Meindl et al. 2013) derived from the non-spherical satellites
  - The strong collinearity of T_Z with residual cross-track bias modeling errors (e.g., SRP) should be taken care of
    - The SRP coefficient should be tuned to reduce aliasing of draconitic errors ($\sim$118 days for Jason-2) into the Z geocenter coordinate
    - The low orbital inclination of the Jason mission reduces this correlation

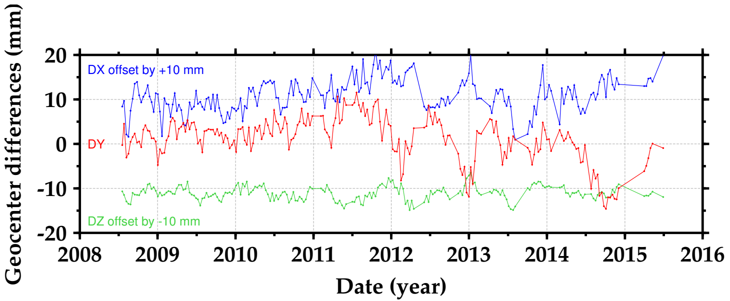
$$T_Z \simeq \frac{-C_{N_0} r^3}{GM \cos i}$$



Solar radiation pressure coefficient C_r of 1.00 versus 1.04

COLLINEARITY ISSUES MITIGATION

- State-of-the-art tropospheric delay model should be used, while mitigating the sensitivity of the DORIS oscillator to radiations
- Mismodeled long-wavelength *Time Varying Gravity* odd-degree order-0 and order-1 terms ($C_{3,0}$, $C_{3,1}$, $S_{3,1}$, ...) may contaminate the recovered geocenter time series (mainly T_X and T_Y)
  - Monthly series of GRACE and GRACE-FO derived geopotential should be used when available



Geocenter differences introduced by the POE-E TVG model vs CSR time series

Comparison to independent estimates

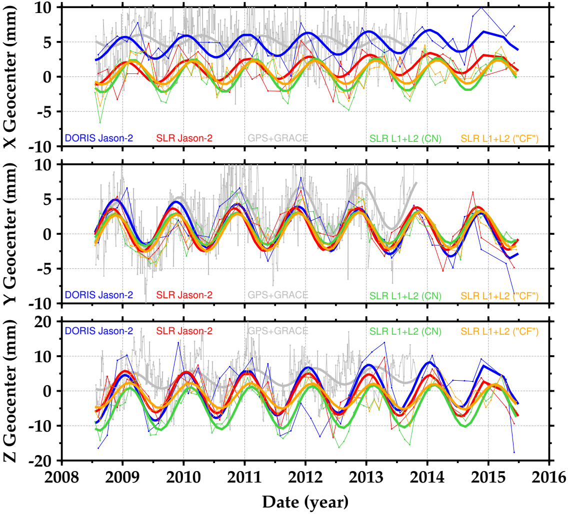
- 1 : GPS+GRACE (Haines et al. 2015), 3-day estimates (*the Z coordinate should be disregarded* because of spurious signals at draconitic periods)
- 2 : SLR L1+L2 (CN) (Ries 2016), 30-day estimates
- 3 : SLR L1+L2 ("CF") (Ries 2016), 30-day estimates
- 4 : DORIS Jason-2 this study, 10-day estimates
- 5 : SLR Jason-2 this study, 10-day estimates

Solution	X		Y		Z	
	A (mm)	ϕ (day)	A (mm)	ϕ (day)	A (mm)	ϕ (day)
1	0.9	105	3.5	334	-	-
2	2.3	61	2.3	317	6.1	41
3	1.7	59	2.7	322	3.6	39
4	1.6	13	3.2	322	6.4	18
5	1.5	21	3.1	302	5.9	21

$\Rightarrow$ The three independent solutions (1-GPS, 3-SLR, 4-DORIS) corroborate to better than 1 mm the annual amplitude along the X and Y axe. Two groups of solutions for the Z amplitude : 3 or 6 mm, where do we stand ?

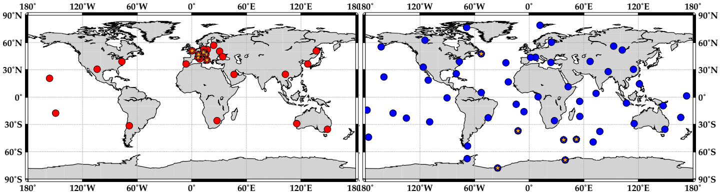
Comparison to independent estimates

- X : Two biases, DORIS/GPS (~ 5 mm) vs SLR (~ 0 mm), network effect ?
- Z : Nongravitational modeling deficiencies of SLR LAGEOS solutions ?



SLR NETWORK EFFECT T_X PERTURBATION

- *Unbalanced network of SLR stations* with most of the high performing stations close to the X axis in the Northern Hemisphere
  $\Rightarrow$ Higher sensitivity of T_X to network effects caused by the geographic distribution of SLR stations (Collilieux et al. 2009)



SLR and DORIS stations used in this study

- Approach : Improve/degrade geometry of the SLR/DORIS stations, removing stations in the Greenwich meridian and high-latitude area
- Results : Increase/lowering of the SLR/DORIS T_X bias

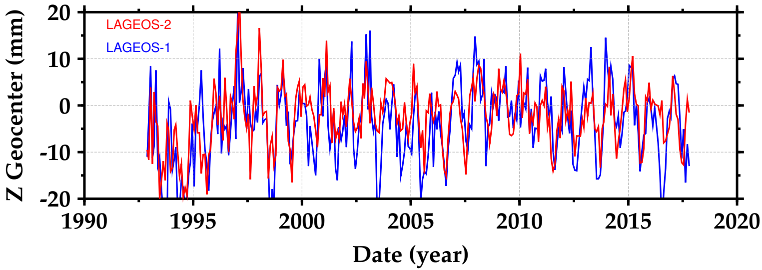
$$1.2\ \text{mm} \Rightarrow 2.4\ \text{mm} / 4.6\ \text{mm} \Rightarrow 2.7\ \text{mm}$$

  - This corroborates the simulation study of Otsubo et al. (2016) indicating that additional SLR sites in the southern high latitudes would benefit T_X

UNCERTAINTY OF THE LAGEOS T_Z

- Monthly Z geocenter motion time series from SLR observations of the LAGEOS satellites *without estimating range biases and station heights*, i.e., consistent with the ILRS contribution to ITRF2014 or the previous CN solution of Ries (2016)
  - The annual signal is obvious

Satellite	T_Z amplitude (mm)	T_Z phase (day)
LAGEOS-1	7.0	35
LAGEOS-2	5.5	29



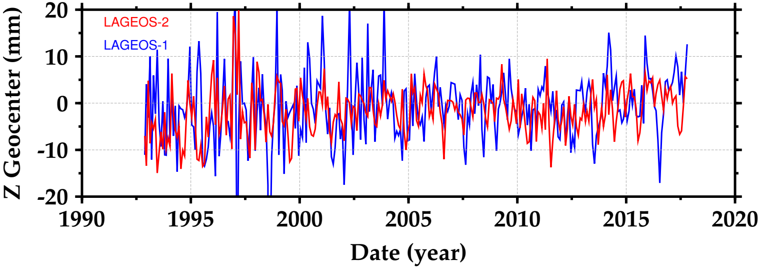
LAGEOS-1 and LAGEOS-2 T_Z estimates without solving for range biases and station heights

UNCERTAINTY OF THE LAGEOS T_Z

cnes

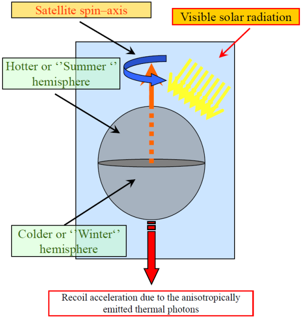
- Monthly Z geocenter motion time series from SLR observations of the LAGEOS satellites *with estimation of range biases and station heights*, i.e., consistent with the previous "CF" solution of Ries (2016), except that *no a priori constraint* has been applied
  - The annual signal almost vanished, as for all spinning satellites...

Satellite	T_Z amplitude (mm)	T_Z phase (day)
LAGEOS-1	2.2	40
LAGEOS-2	2.6	22



LAGEOS-1 and LAGEOS-2 T_Z estimates when solving for range biases and station heights

- ***Yarkovsky-Schach* effect**
  - The Yarkovsky-Schach thermal effect affects spinning satellites essentially along their spin axis



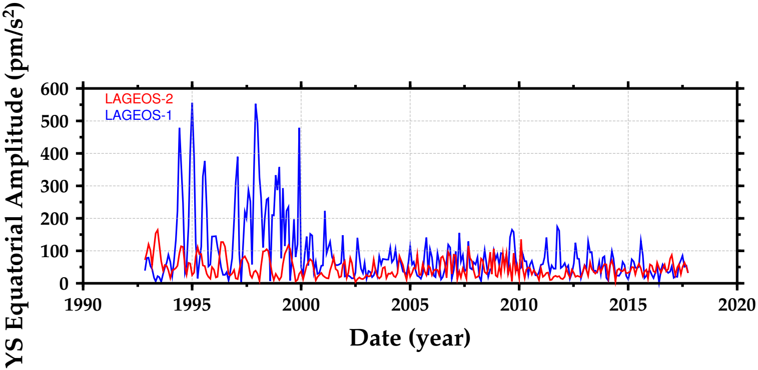
YS force directed along the spin axis, away from the heated pole (Lucchesi et al., 2003)

  - This perturbation is usually not modeled in orbit determination programs since the evolution of the satellite spin axis is not precisely known as well as its amplitude itself
    - Afonso et al. (1989) : $59\ \mathrm{pm.s}^{-2}$, Scharoo et al. (1991) : $89.4\ \mathrm{pm.s}^{-2}$, Slabinski (1996) : $105\ \mathrm{pm.s}^{-2}$, Metris et al. (1997) : $241\ \mathrm{pm.s}^{-2}$, ...

UNCERTAINTY OF THE LAGEOS T_Z

cnes

- An updated estimate of the Yarkovsky-Schach amplitude can be obtained from the adjustment of two orthogonal accelerations along inertial directions in the equatorial plan of the Earth
  - Annual variations exhibit in the YS equatorial amplitude because of the seasons (Earth's equator being tilted w.r.t. the ecliptic)

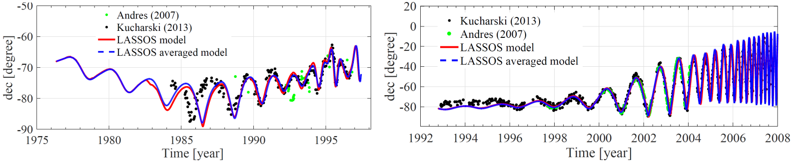


LAGEOS-1 and LAGEOS-2 amplitudes of their inertial equatorial perturbing accelerations

UNCERTAINTY OF THE LAGEOS T_Z

- A *complete picture of the YS amplitude* can be obtained from the previous equatorial amplitude estimates and the directions of the LAGEOS-1 and 2 spin axes provided below
  - The YS thermal accelerations could reach $\sim 900\ \mathrm{pm.s^{-2}}$ and $\sim 600\ \mathrm{pm.s^{-2}}$ for LAGEOS-1 and 2, respectively
  - When projected on their associated cross-track direction, these estimates of the YS annual perturbations corrupting the Z geocenter coordinate can definitely explain the ~ 5 and $\sim 3\ \mathrm{mm}$ reductions in LAGEOS-1 and 2, respectively, geocenter motion time series

$$Z_{\text{Y-S}_{\text{Annual Error}}} \simeq A_{\text{Y-S}} \frac{r^3}{GM}$$



LAGEOS-1 (left) and LAGEOS-2 (right) declinations of their spin axis (Visco and Lucchesi 2018)

CONCLUSION

- Jason satellites are unique DORIS satellites : *recommendations for future "geocenter-dedicated" missions*
  - Inclination much below $90°$
  - Draconitic period not close to one solar year
  - No fixed attitude (yaw steering motion)
  - Possibility to initiate an independent geocenter time series in 1992 with T/P

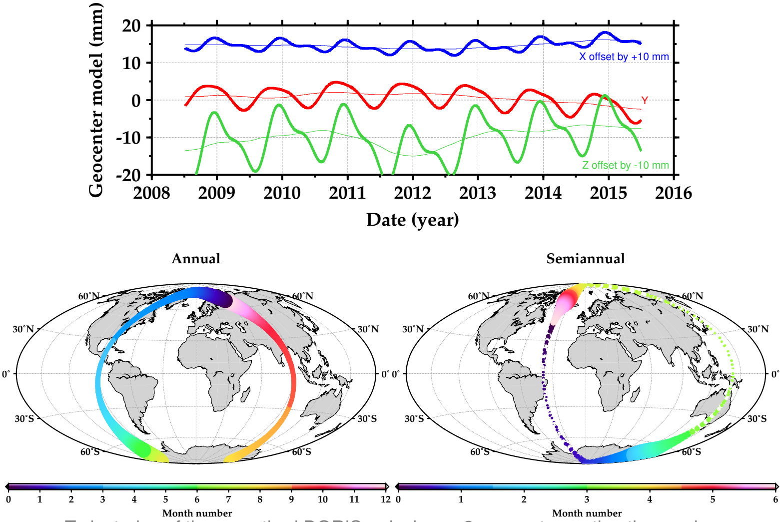
  $\Rightarrow$ The future consecutive launches of HY-2C (inclination of $66°$), Jason-CS/Sentiel-6, and SWOT (inclination of $78°$, draconitic period of 78.5 days) will make possible a combination

- Current *LAGEOS-only realization of the ITRF origin* :
  - Could be biased of ~ 5 mm in the X direction
  - Annual amplitude uncertainty of the geocenter coordinates below 1 mm for the equatorial components and of ~ 3 mm in the Z direction

$\Rightarrow$ DORIS contribution to geocenter motion determination may/should play a role for future ITRF realizations

Modeling the full non-tidal geocenter

- Having an accepted model for POD becomes a prerequisite



Trajectories of the smoothed DORIS-only Jason-2 geocenter motion time series