SLR-based geocenter estimates with atmospheric pressure station loading (APL) and other corrections for improved orbit centering

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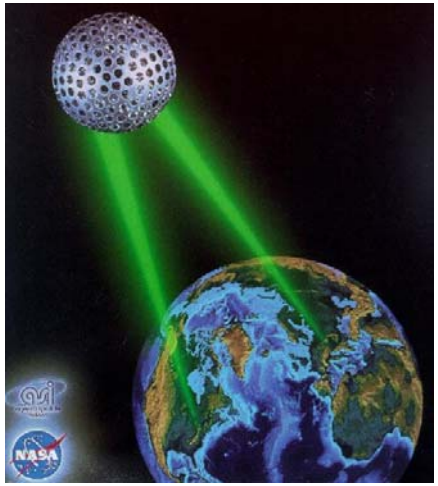

OSTST POD
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Goal: improved SLR+DORIS orbit centering through an improved SLR determination of CM

1) **CM-CN** (Earth Center of Mass - Center of Network) estimated in GEODYN using geometrical translation between the station network CN and observed satellite orbit CM positions.

1) **LAGEOS 1+2 data** and SLRF2014 used for 28-day CM estimation from 1992.8 up to 2016.0

1) **LAGEOS SLR corrections** tested address 'Network Effect':
    1) non-tidal Earth surface deformations in computing CN (**empirical accommodation** and direct **APL forward-modeling** (APL from JP Boy))
    2) SLR station range error estimation
    3) SLR station timing error (from T2L2)

1) **Orbit centering** improvement evaluated using Jason-2 SLR+DORIS estimates of residual CM.

LAGEOS 1+2 GEODYN CM estimation tests

Test Name	
biasprv (Classical)	GSFC2014 SLR bias estimation POD strategy (based on ILRS SLRF2008/2014 recommendations). *Probably similar to strategies used at other Analysis Centers to empirically remove specific station range error*
nobias	no biases estimated
biasprv_apl	biasprv + Atmosphere Pressure Loading *Forward-model atmosphere loading station deformation*
biasprv_apl_t2l2	biasprv_apl + T2L2 station time tag correction (July 2008 - 2016)
nobias_apl	nobias + Atmosphere Pressure Loading
mbias	Estimate range bias/ arc for all stations (Appleby et al. 2016); *Empirically remove station range error + accommodate station position non-tidal surface deformation.*
mbiasc01	mbias + Bayesian constraint bias estimate of 1-cm
nobias_stah	nobias + estimate station heights (2-cm constraint)

GSFC Classical (biasprv) annual CM model
Very close to other recent SLR-based models

Recent SLR CM solutions	Amplitude (mm)			Phase (degrees)		
	X	Y	Z	X	Y	Z
GSFC Classical (biasprv) LAGEOS 1+2; ITRF2014 (1992.8-2016)	2.3	2.6	6.2	48	319	33
Ries (2016) LAGEOS 1+2; ITRF2014 (1993-2016)	2.4	2.5	6.1	55	321	31
Altamimi et al (2016); ILRS contribution to ITRF2014 (1993-2015)	2.6	2.9	5.7	46	320	28
Ries (2013) POD standard; 4 SLR-model average	2.7	2.8	5.5	41	321	27

Annual SLR-based CM models which do NOT address non-tidal station loading (CM-CN; Amp*cos(θ-phase))

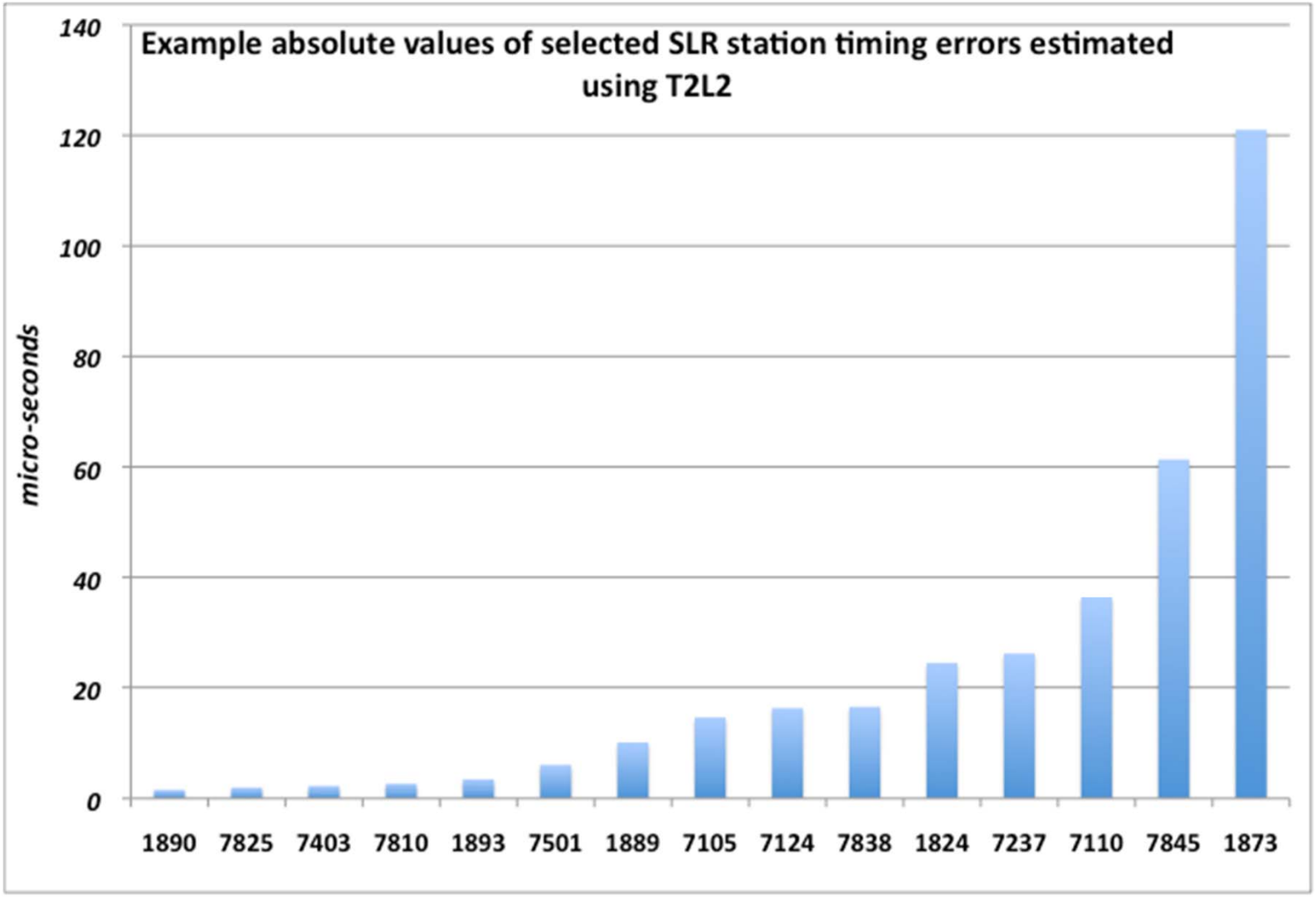
Annual CM model		Amplitude (mm)			Phase (degrees)		
		X	Y	Z	X	Y	Z
biasprv	1992.8-2016	2.3	2.6	6.2	48	319	33
biasprv	2008.5-2016	2.9	2.5	5.4	53	303	46
nobias	2008.5-2016	2.8	2.3	6.9	56	305	31
Ries (2013)	model average (15+ years)	2.7	2.8	5.5	41	321	27

To be tested with Jason-2 and NO forward-modeling of APL (effect of non-tidal loading absorbed in CM estimate)

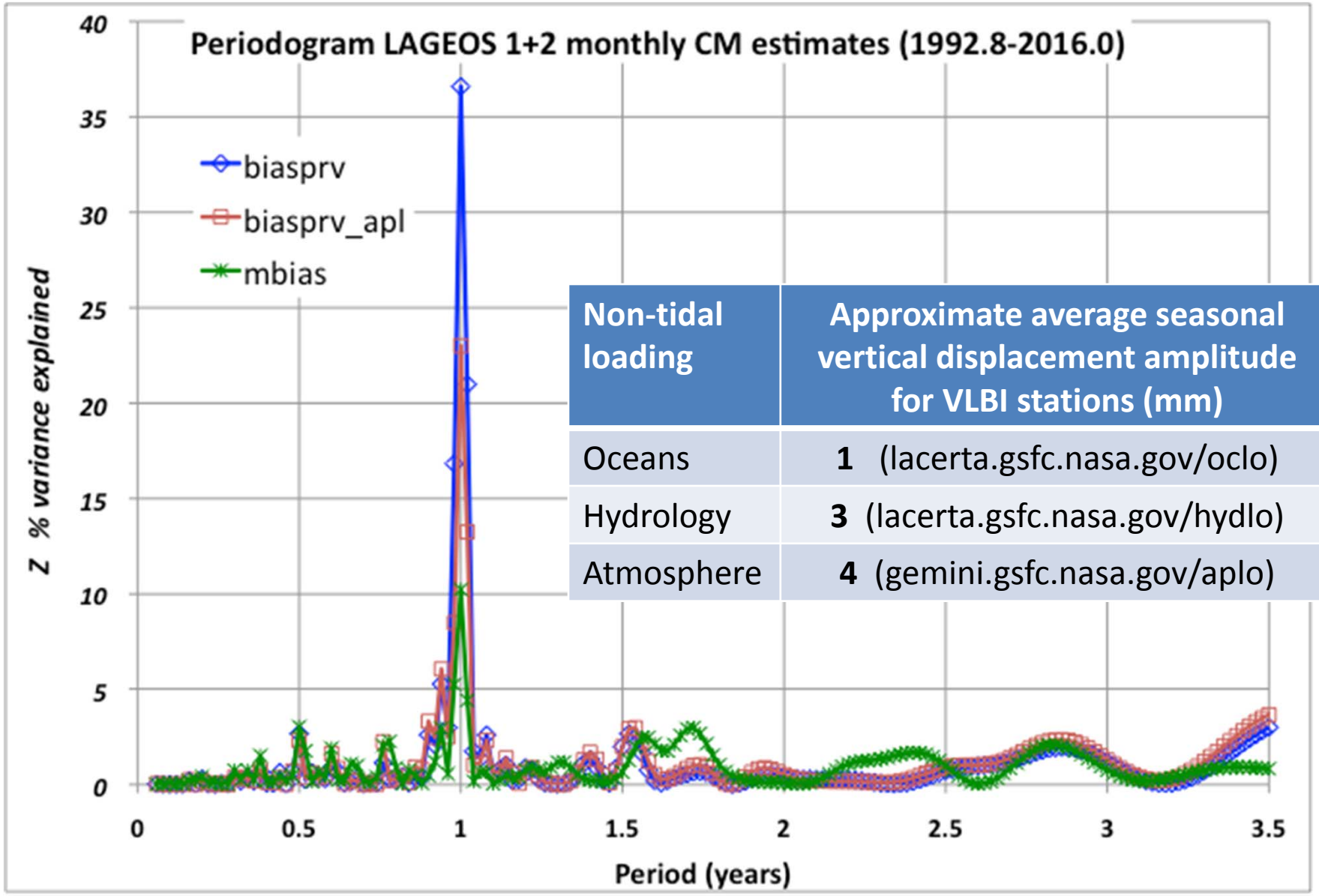
T2L2 SLR Station Timing Corrections Illustration

Timing correction to offset and drift station determined over specific periods using Jason-2 T2L2 data and Grasse hydrogen maser

(see A. Belli presentation)



CM estimate series show almost all power in annual term (non-tidal station loading includes a degree-1 component)



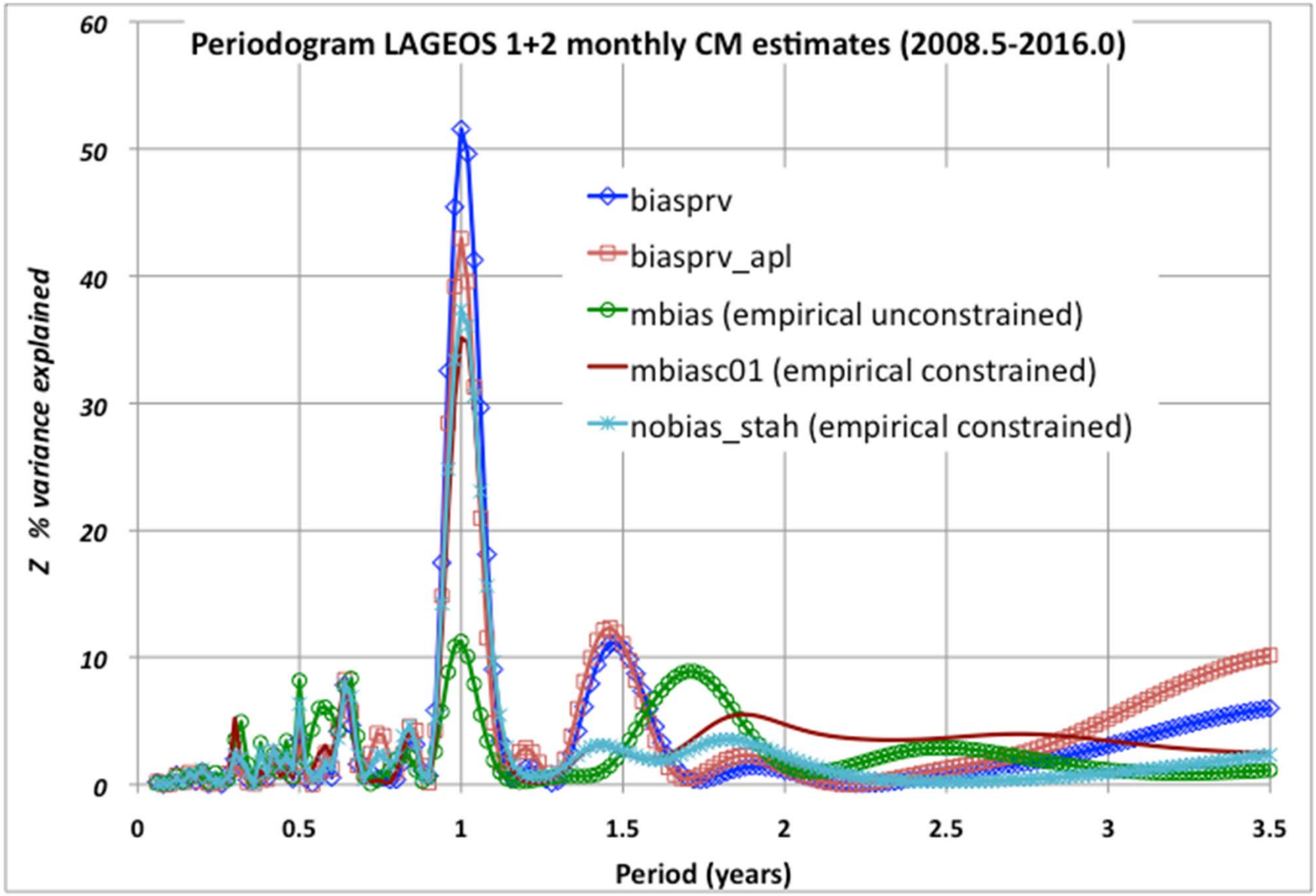
Non-tidal loading	Approximate average seasonal vertical displacement amplitude for VLBI stations (mm)
Oceans	**1** (lacerta.gsfc.nasa.gov/oclo)
Hydrology	**3** (lacerta.gsfc.nasa.gov/hydlo)
Atmosphere	**4** (gemini.gsfc.nasa.gov/aplo)

Annual SLR-based CM models which DO address non-tidal station loading (CM-CN; Amp*cos(θ-phase))

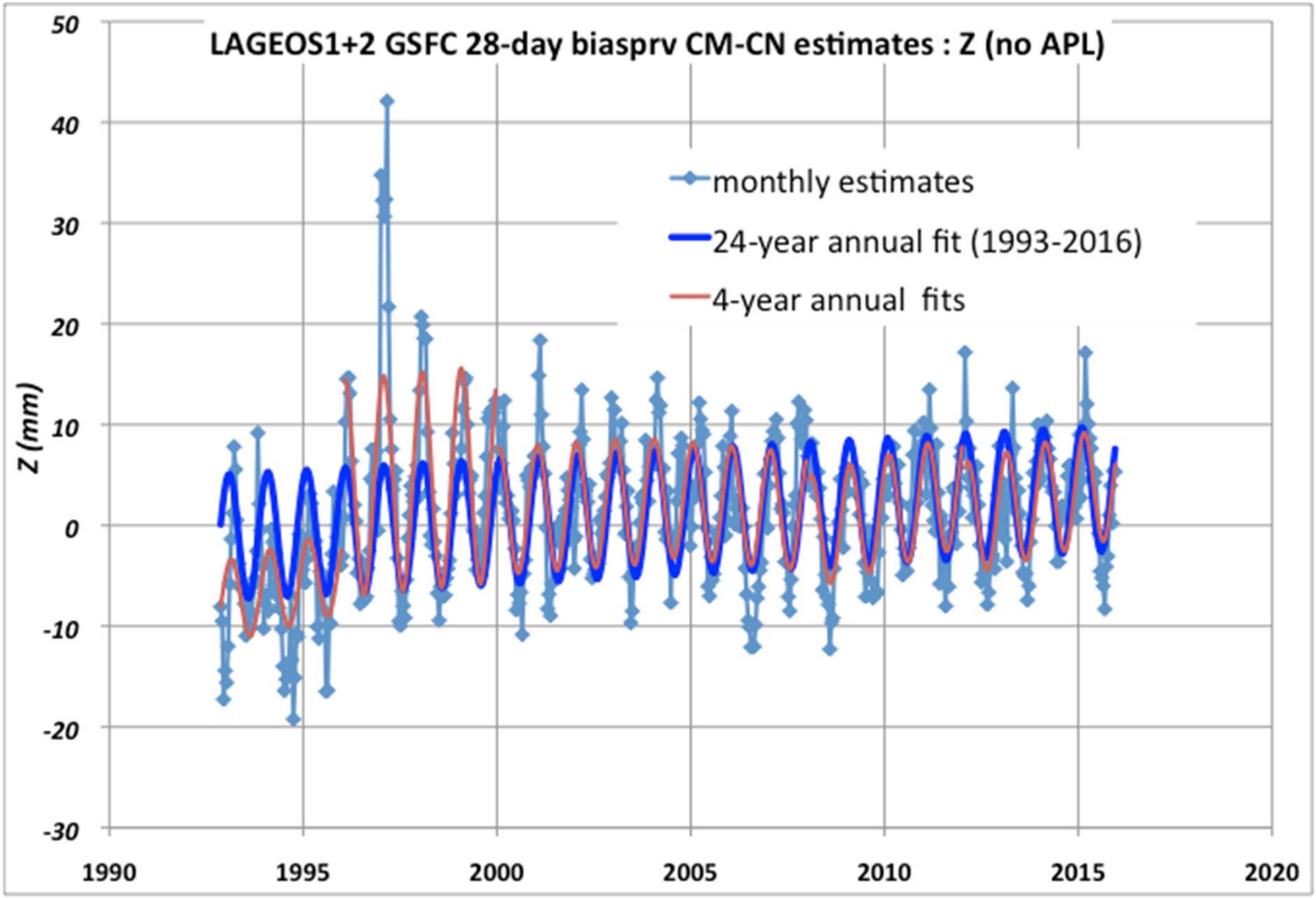
GSFC Annual CM model		Amplitude (mm)			Phase (degrees)		
		X	Y	Z	X	Y	Z
biasprv_apl	1992.8-2016	1.9	1.9	4.2	70	301	54
biasprv_apl	2008.5 -2016	2.6	2.1	4.2	66	282	69
biasprv_apl_tbt2l2	2008.5 -2016	2.5	2.1	4.2	66	281	66
nobias_apl	2008.5 -2016	2.6	1.9	4.6	67	294	49
mbias	2008.5 -2016	1.5	2.6	1.9	51	311	29
mbiasc01	2008.5 -2016	1.2	1.9	2.8	55	315	8
nobias_stah	2008.5 -2016	1.7	2.7	3.7	49	310	30

To be tested with Jason-2 and with forward-modeling of APL

Unconstrained empirical compensation for non-tidal loading greatly weakens the CM-CN translation estimate



Annual signal in CM monthly series changes in amplitude and phase over time - due to geophysical causes?
Is an annual model the best choice?



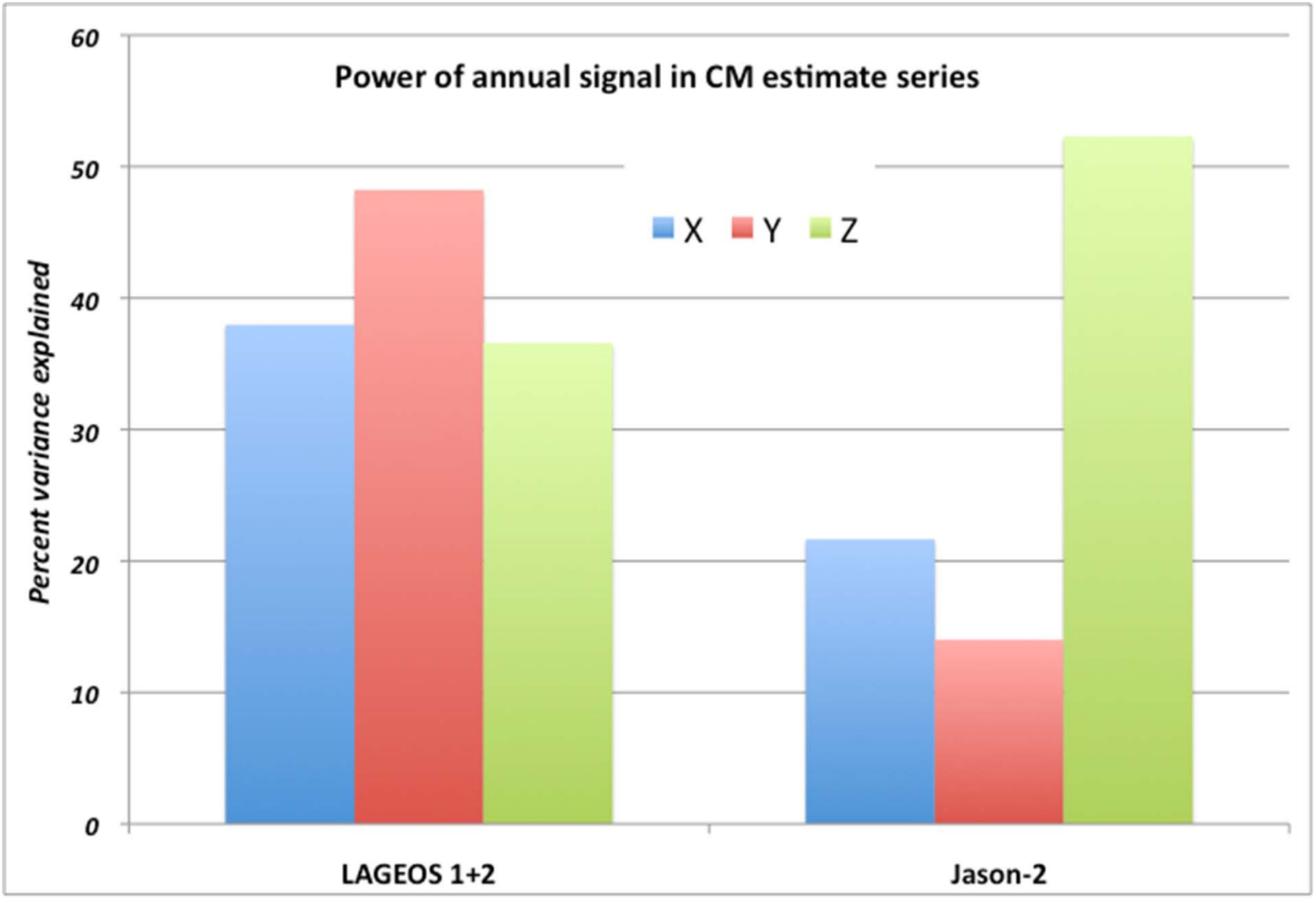
Is the computed orbit origin now better aligned with the instantaneous center of mass ?

Test with

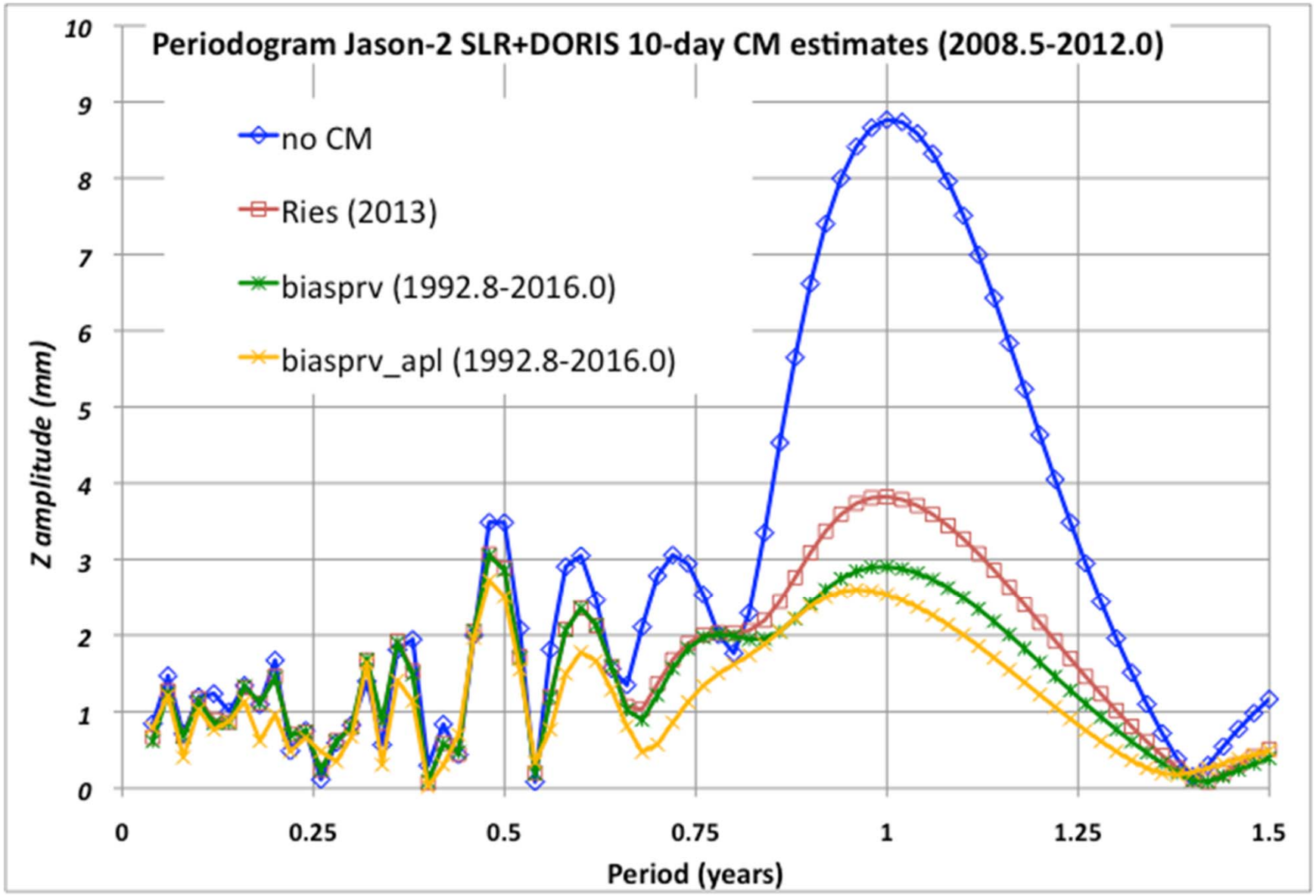
Jason-2 SLR+DORIS estimates of residual CM:

The smaller the residuals- the better the background CM model

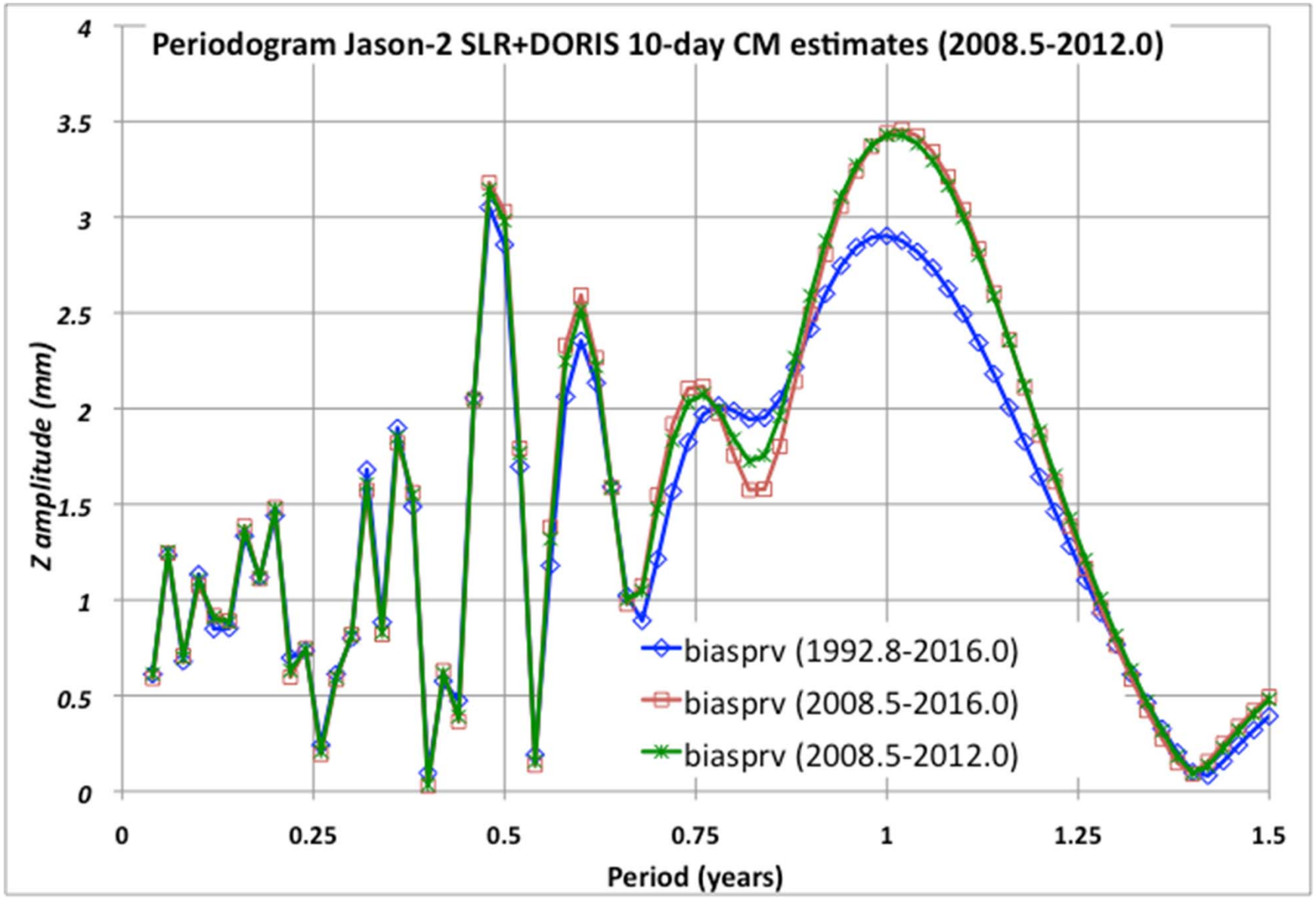
Rely on LAGEOS 1+2 sensitivity to CM - to estimate model
Rely on Jason-2 sensitivity to CM - to test orbit centering



Residual Jason-2 CM estimates indicate - forward-modeling APL is beneficial

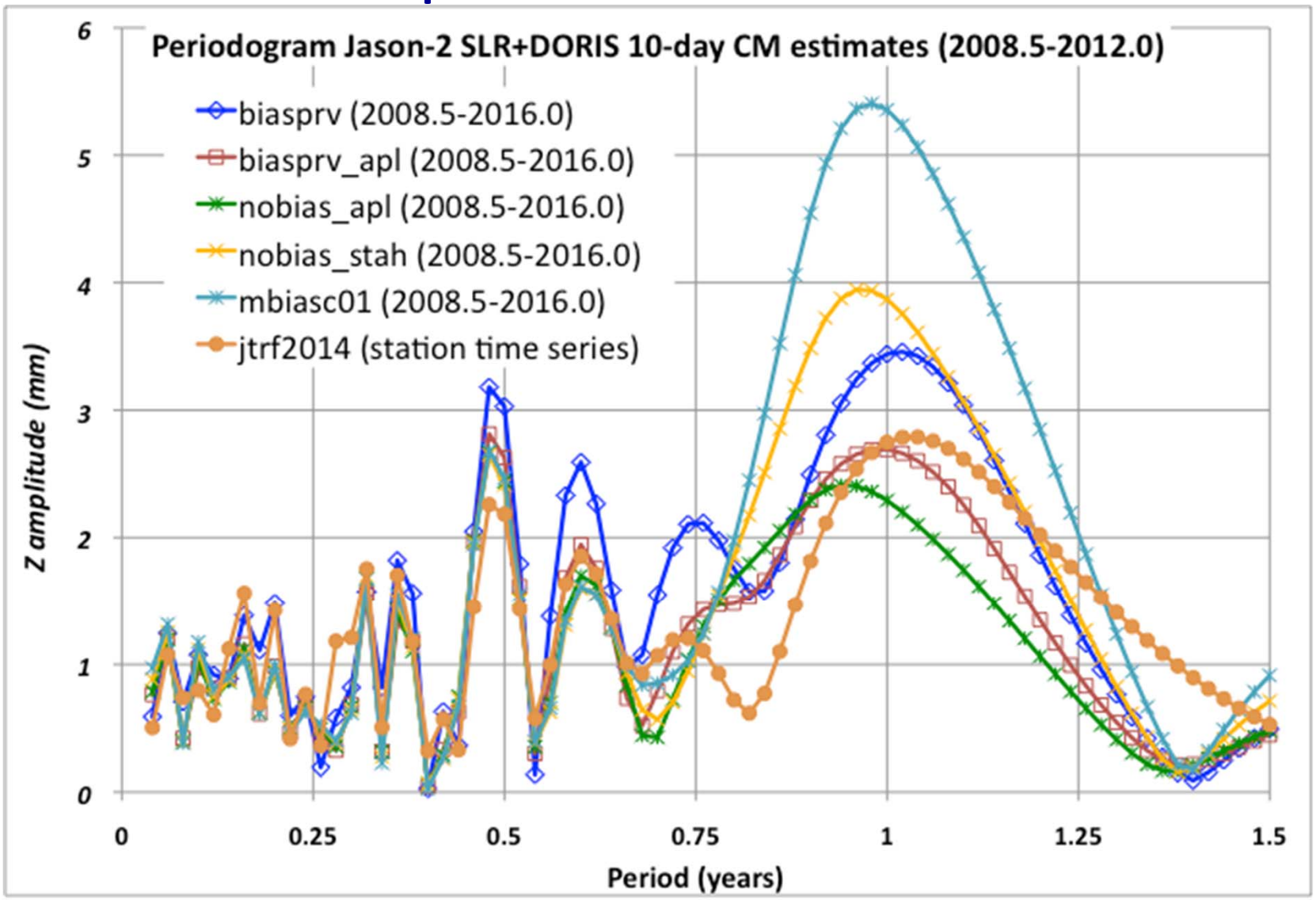


Residual Jason-2 CM estimates indicate - a closer annual CM fit to the test period does not help



Residual Jason-2 CM estimates indicate -

- empirical corrections to SLR range do not help CM estimates
- CM time series implied in JTRF2014 is not the best model



Conclusions

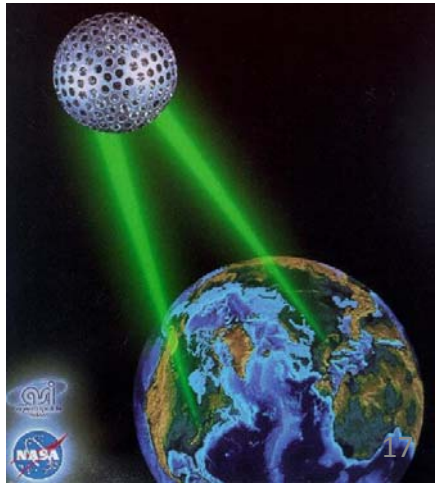
Recap CM test model orbit centering results:

1) improved with LAGEOS APL forward-modeling
2) improved with CM annual model estimated over the longer time series (24 years)
3) JTRF2014 smoothed weekly station position time series (Abbondanza et al 2017) do not show the best orbit centering.
4) empirical corrections to LAGEOS range data impair CM model orbit centering

Implications of preliminary test results:

1) Other than for the annual and semi-annual geophysical signals, the LAGEOS SLR CM series are noisy. The effects of SLR range error contribute to the noise.
2) Estimation of SLR range biases impairs the CM estimate.
3) Better to accurately model non-tidal loading at observation level, than to allow CM estimate to absorb the effect

Thank you



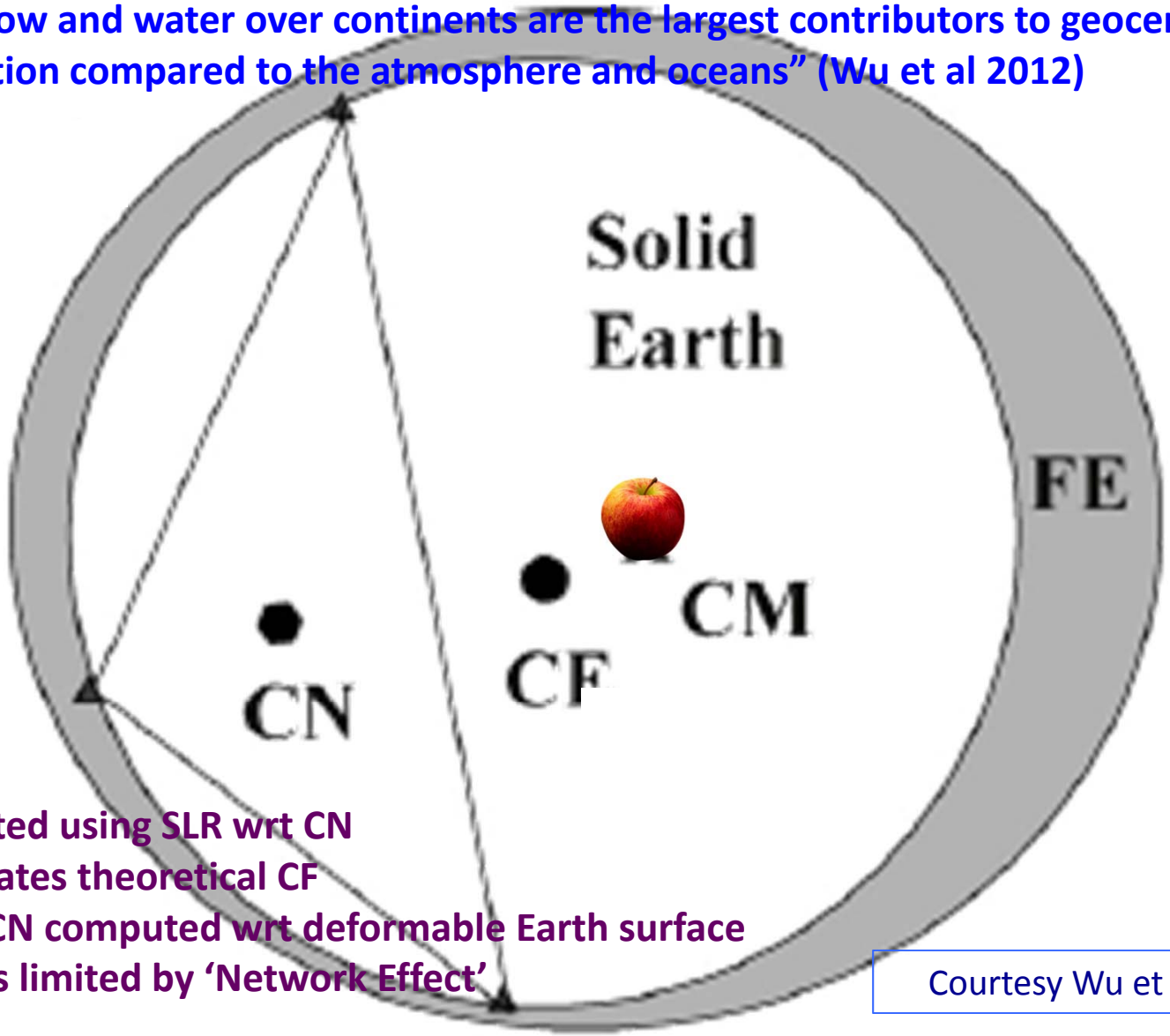
BACKUP

GSFC CM Estimate
LAGEOS 1+2 combined solution modeling

0. IERS2010 (pole).
1. SLRF2014 (stations). Elcut 12 deg.
2. GOT4p10 (ocean tides
3. Earth Tides. IERS2003
4. GOT4p10 (ocean loading).
5. Mendez model for SLR troposphere correction
6. Tidal EOP
7. Tidal Geocenter (GOT4p7).
8. Gravity. GOCO2S (static) + TVG (5x5 weekly solutions) +Annual terms from GRACE for L >= 5.
9. Adjust opr along/cross + along-track constant/week for L1 & L2.
10. Adjust biases/station (combined for L1+L2) per GSFC2014 strategy, or as specified by test.
11. Station specific satellite center of mass corrections (G. Appleby)
12. Atmosphere Pressure Loading (Jean-Paul Boy, ECMWF) applied as specified.

Earth Center of Mass (CM), Center of Figure (CF), Center of Network (CN)

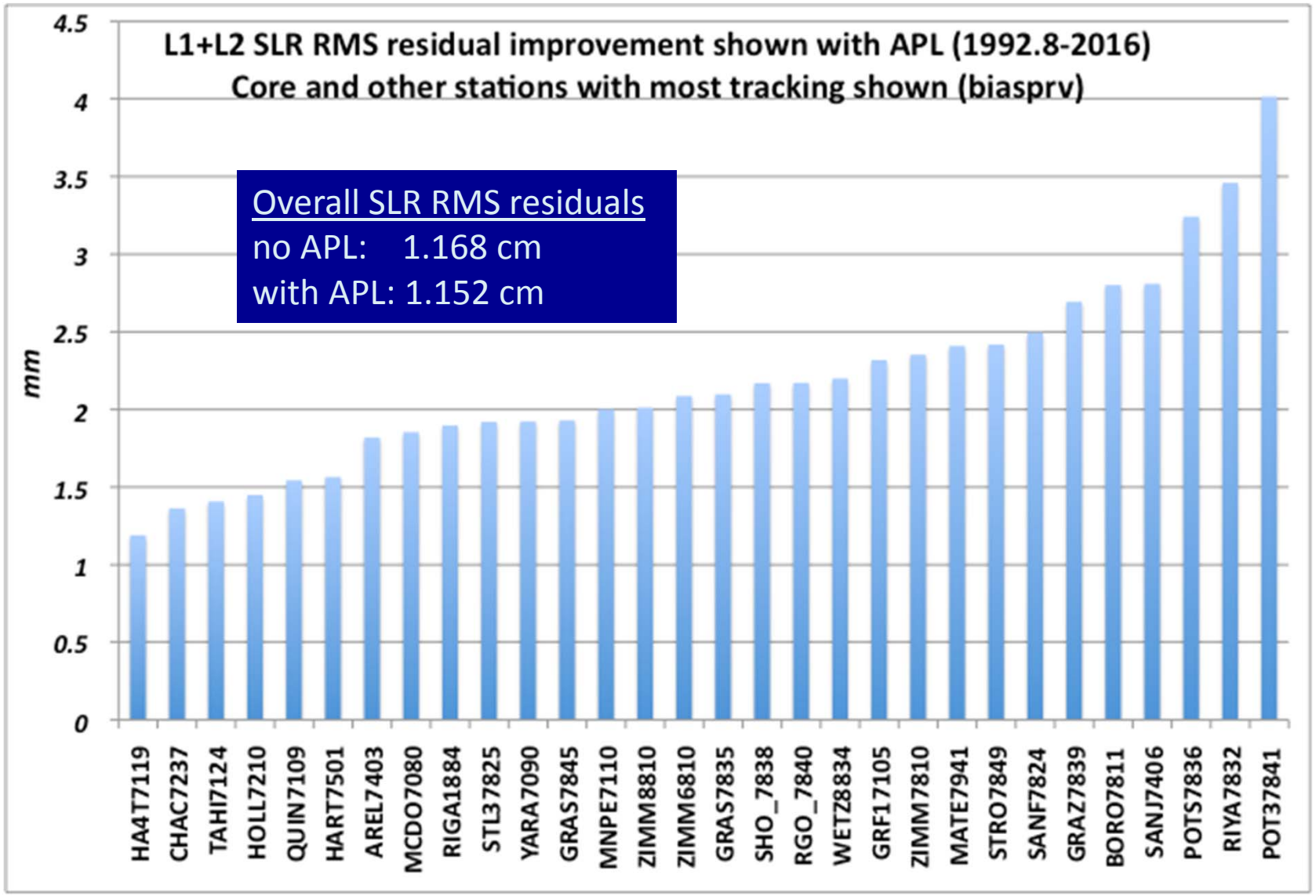
"Snow and water over continents are the largest contributors to geocenter motion compared to the atmosphere and oceans" (Wu et al 2012)



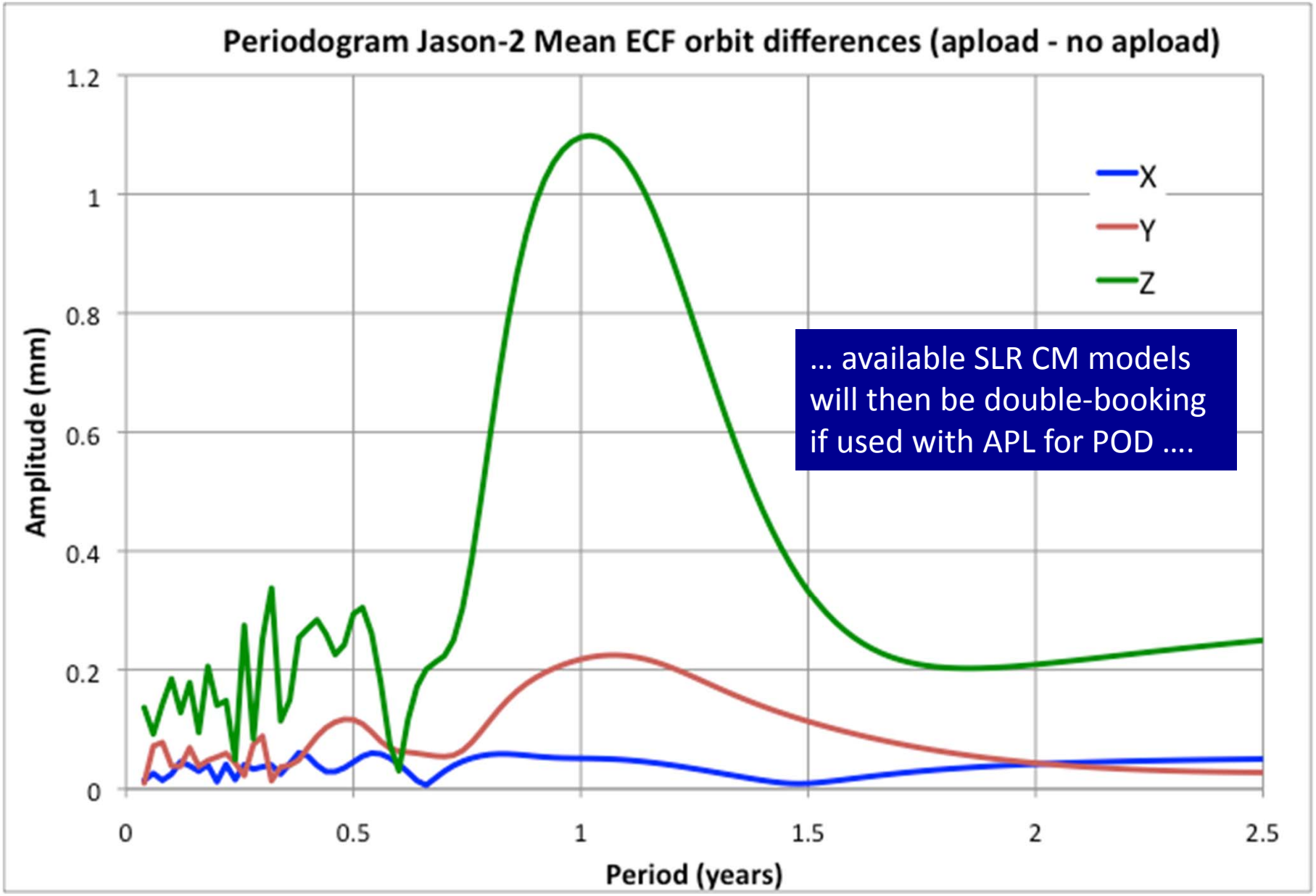
- **CM is estimated using SLR wrt CN**
- **CN approximates theoretical CF**
- **CF & ideally CN computed wrt deformable Earth surface**
- **SLR estimates limited by 'Network Effect'**

Courtesy Wu et al., 2012

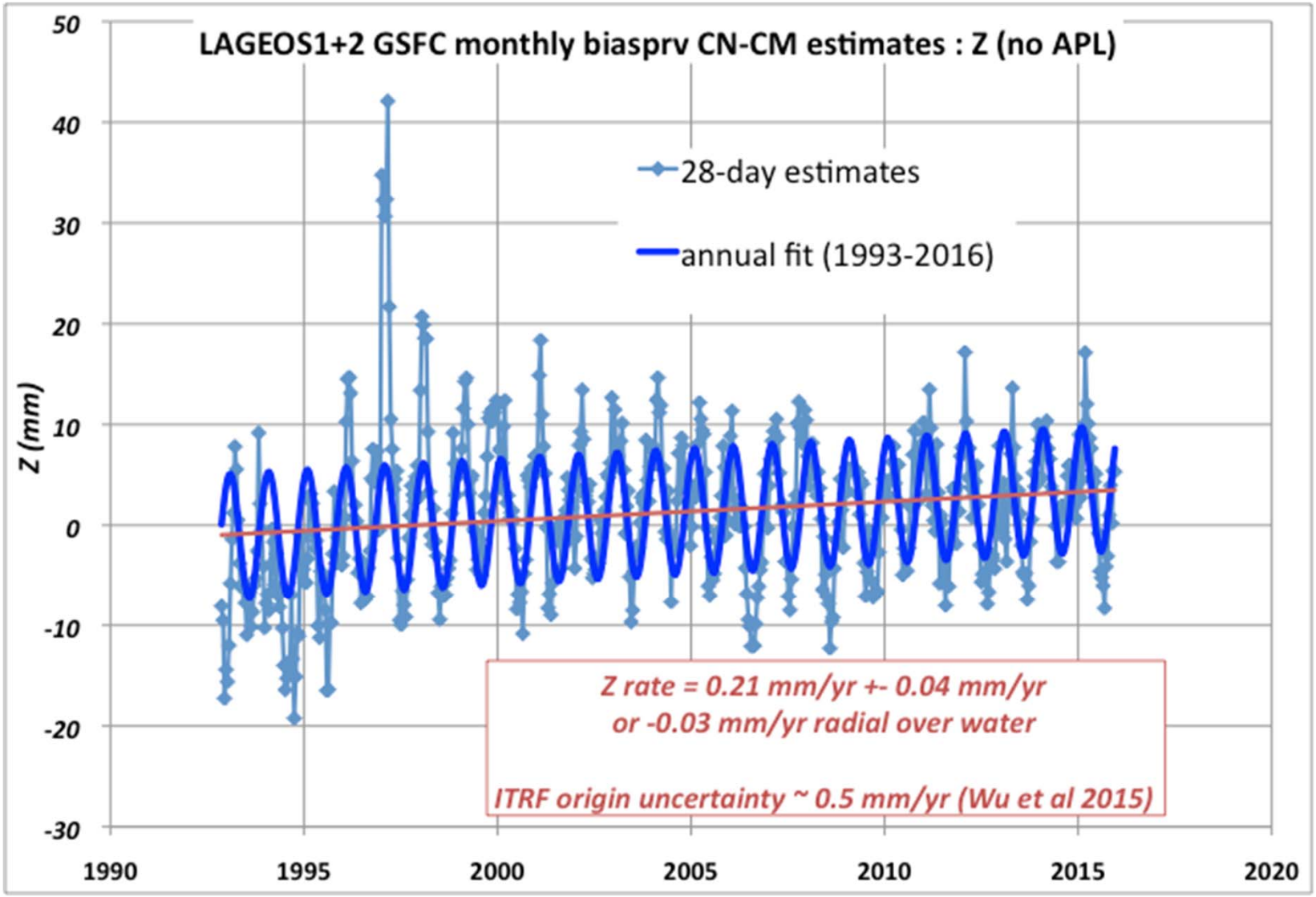
Atmospheric Pressure Loading (APL) improves LAGEOS 1+2 SLR residuals by 2 mm RMS overall (1992.8-2016)



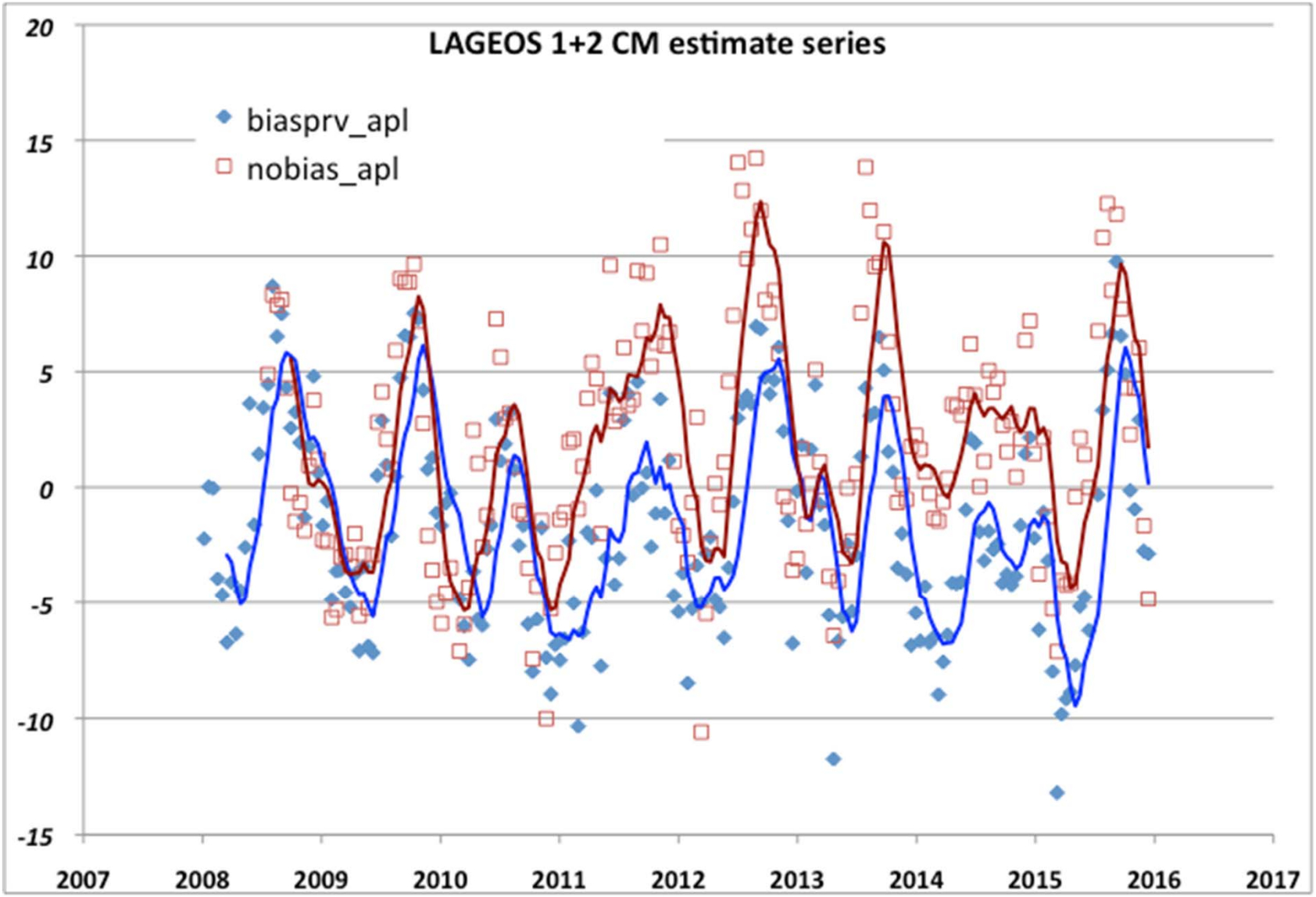
Atmosphere Pressure Loading (APL) includes a Degree-1 Component absorbed in available SLR CM models



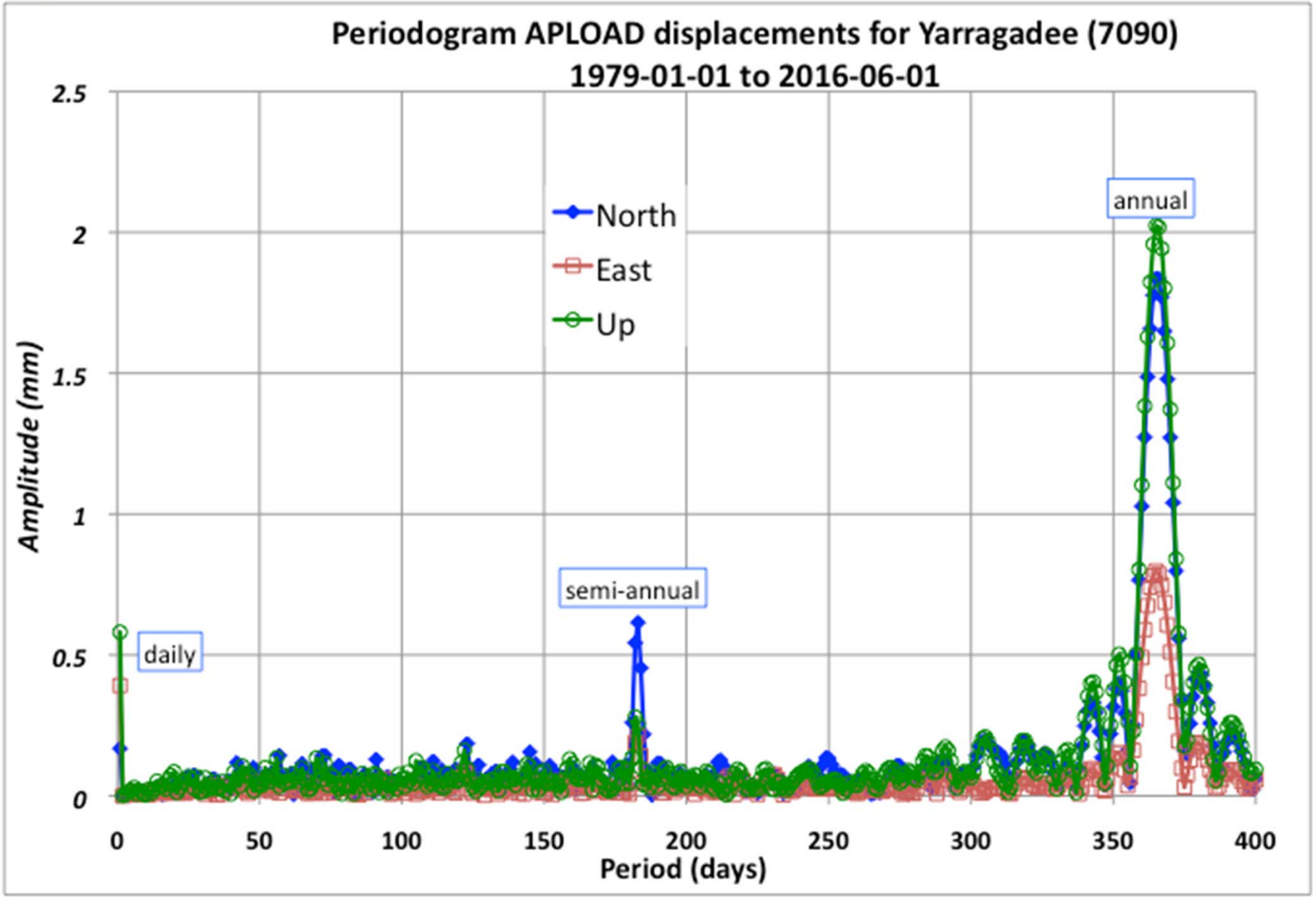
Secular rates found in GSFC SLR CM estimate series appear to have statistical significance; Secular rates for other CM series are not reported



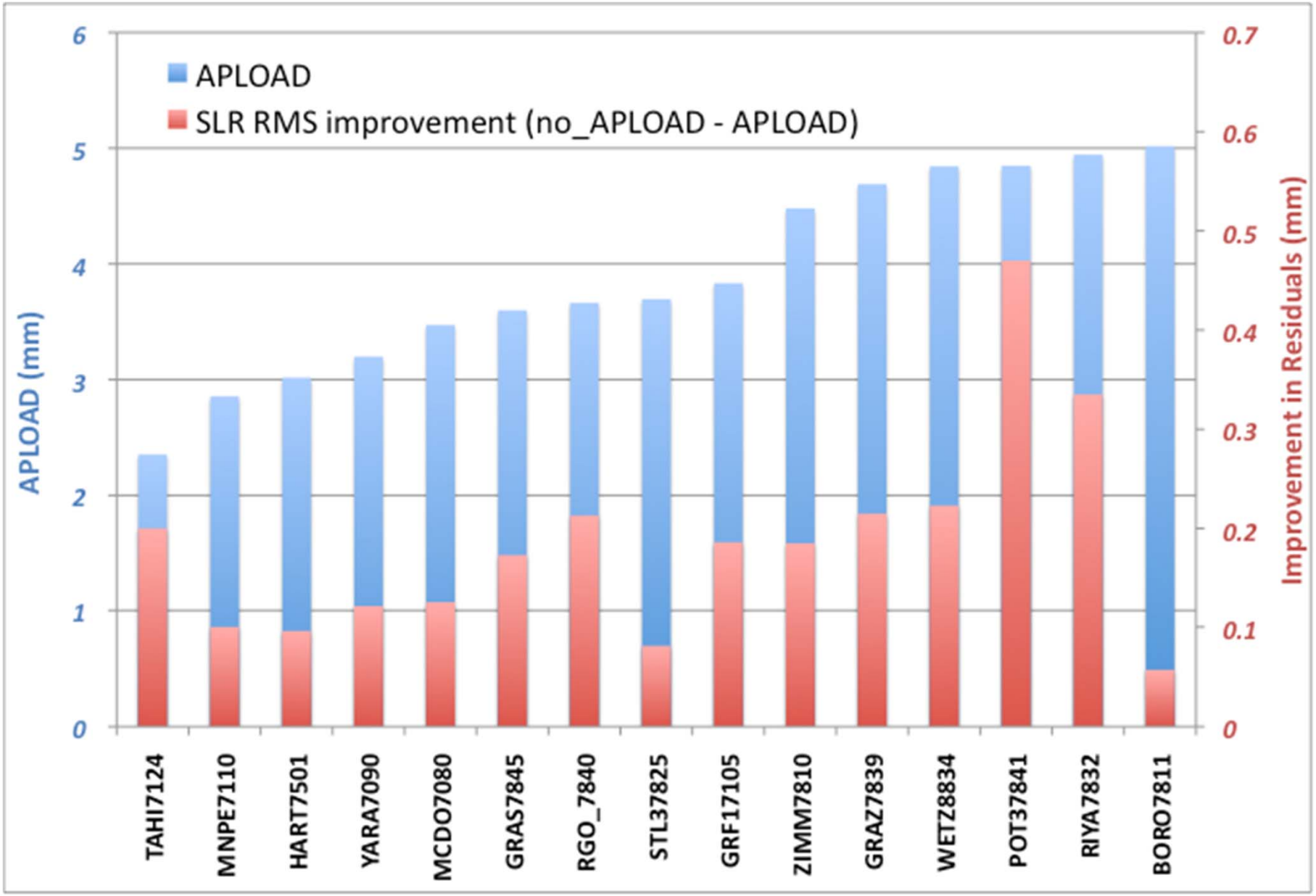
“nobias” CM series have most pronounced annual signal
SLR errors probably have a random distribution



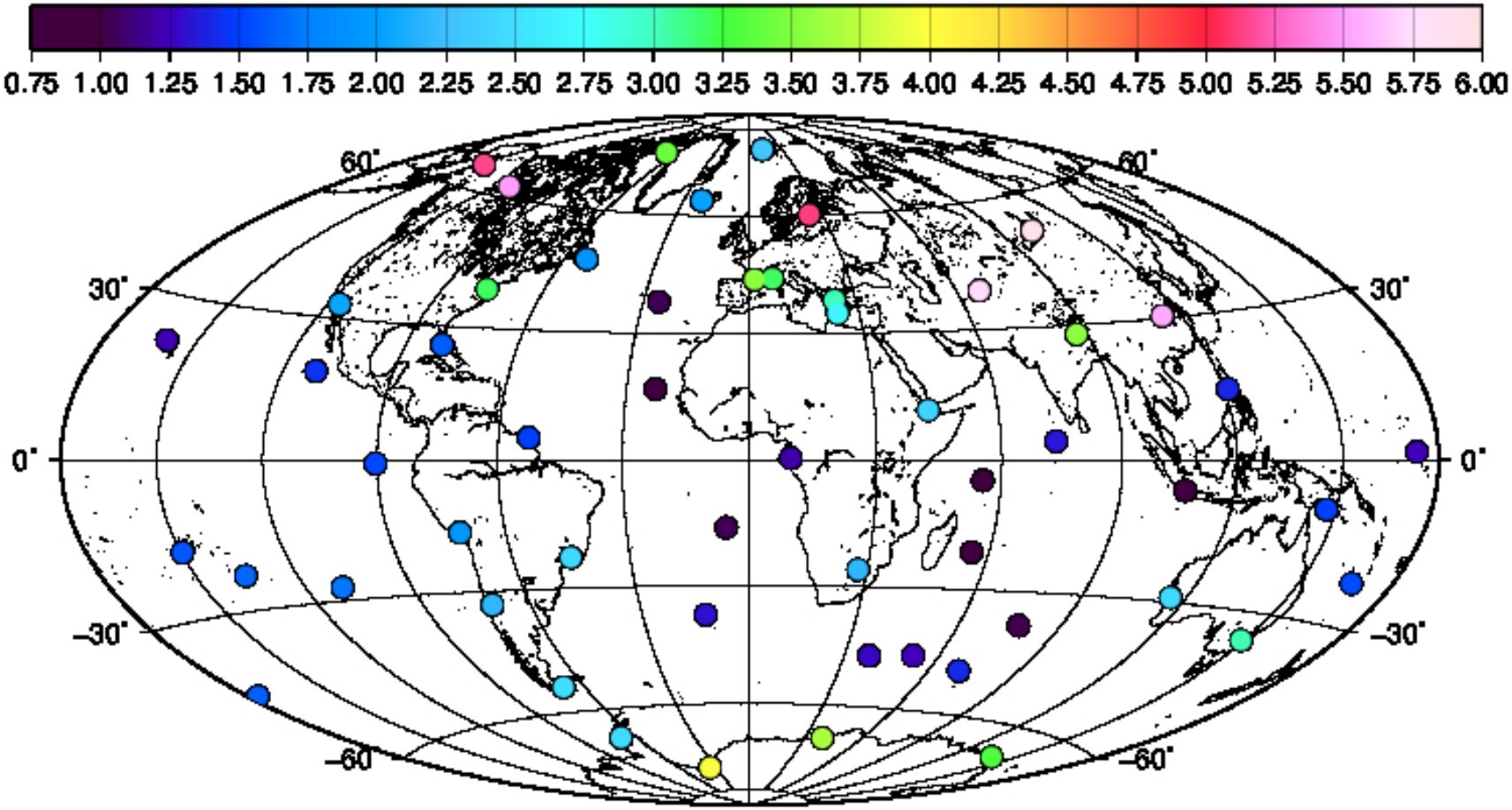
Atmosphere Pressure Loading signal example



Atmosphere Pressure Loading and Improvement in LAGEOS-1/2 SLR Residuals (2008-2011)



Atmosphere Station Loading RMS vertical deformation corrections at 55 DORIS stations over 2008-2011 (mm)

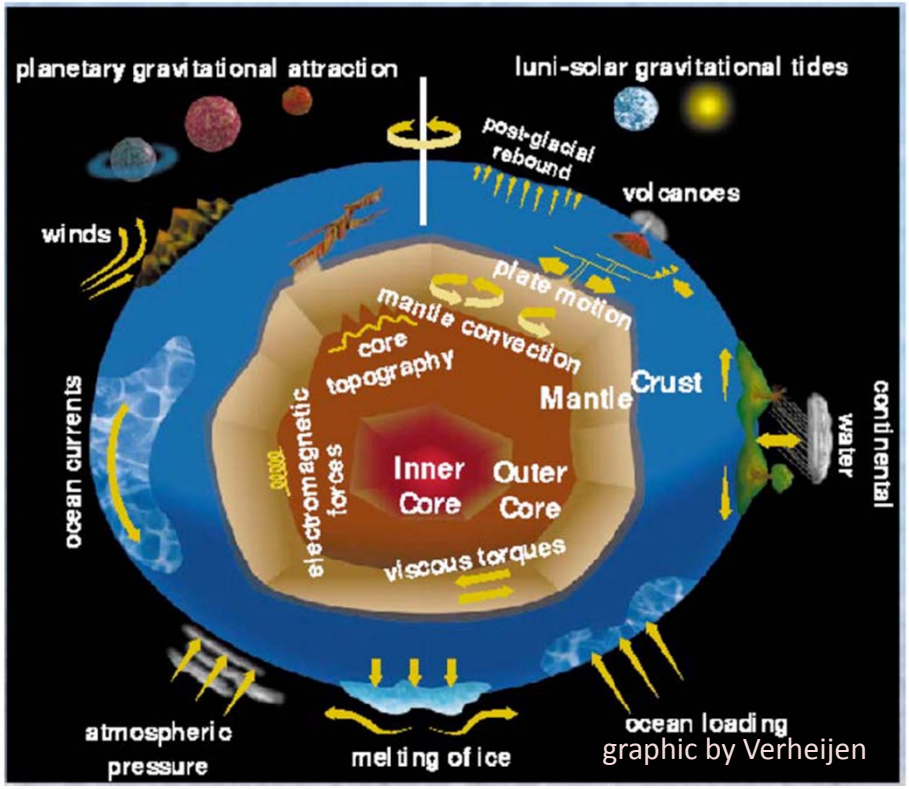


Atmosphere loading corrections provided by Tonie van Dam in N, E, Up

Conceptually CM is referenced wrt CF, and estimated with SLR wrt CN – all are changing

In the **solid** Earth center of mass frame, geocenter motion of the Total Earth's mass referenced to CF:

$$r_c(t) = r_{cm}(t) - r_{cf}(t)$$



$r_{cm}(t)$: displacement of the center of mass (CM) largely due to redistribution of continental water, atmospheric and oceanic mass at the Earth's surface.

$r_{cf}(t)$: displacement of the center of figure (CF) due in large part to elastic deformation of the Earth's surface caused by loading.