From satellite antenna Centers of Phase to the Center of the Earth: a study in improving the modeling of SLR/DORIS antenna phase centers and of the geocenter

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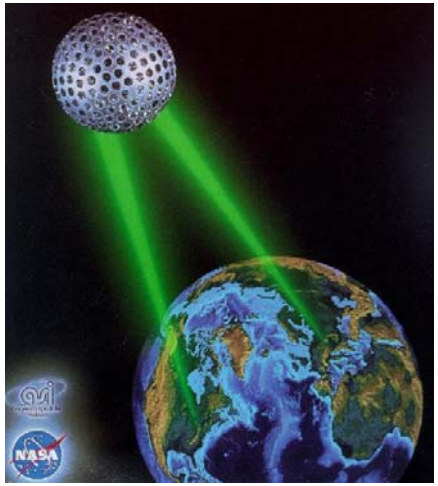


OSTST POD
Ponta Delgada, Azores
September 27, 2018

Analysis Goal:

Improve altimeter orbit centering alignment to Earth's Center of Mass (CM)

Analysis Questions:

1) **CM estimate sensitivity with SLR and DORIS data?**

2) **Computed orbit origin sensitivity?**

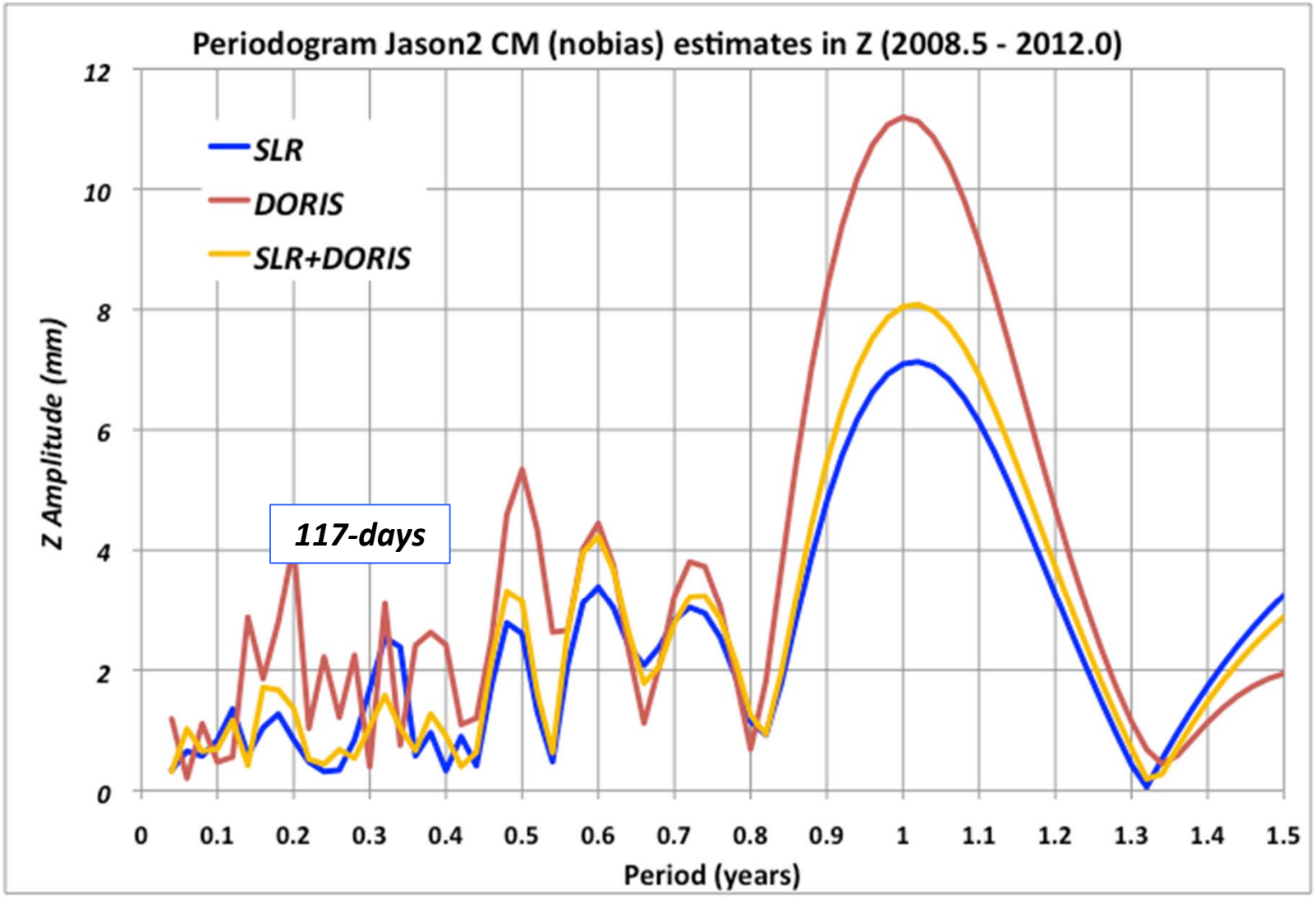
1) **How can we know when the computed orbit origin is best aligned with the Earth's CM?**

Analysis Method: CM-CN (Earth Center of Mass - Center of Network) estimated using ***geometrical translation*** between the station network CN and observed satellite orbit CM positions. Simultaneously estimated with orbit, force and measurement parameters.

Periodogram J2 SLR/DORIS CM estimates in Z (2008.5-2012.0)

(no SLR biases, 1 OPR per day are estimated)

How similar are CM estimates between SLR - DORIS?



Annual fits to J2 SLR/DORIS CM estimates (2008.5-2012.0)

(no SLR biases, 1 OPR per day are estimated)

Agreement overall is pretty good!

However some differences (in red) need to be better understood

Data	Bias treatment	Amplitude (mm)			Phase (deg)		
		X	Y	Z	X	Y	Z
SLR	nobias	4.3	2.1	7.0	40	306	36
DORIS	ebias	2.3	3.2	10.7	112	333	24
SLR + DORIS	nobias + ebias	3.2	2.0	8.0	45	319	34

ebias: GEODYN partitioning of "nuisance" biases used to correct the data, but not carried in the total solution matrix.

We will now move on to look at CM sensitivity to some aspects of SLR/DORIS processing

Annual fits to J2 SLR+DORIS CM estimates (2008.5-2016.0)

(podbias+ebias processing)

-TEST sensitivity to OPR empirical acceleration estimation

- *CM estimates are somewhat sensitive to empirical parameter strategies (table below)*
- *Some correlation between OPR and CM XYZ estimates (to -0.61)*
- *Correlation between CM XYZ estimates increases with increase in number of OPR estimates (to 0.45, back-up slides)*
- *Annual gravity error orbit signal may confound CM estimation (later slide)*

Frequency along/cross-track OPR acceleration adj.	Amplitude (mm)			Phase (deg)		
	X	Y	Z	X	Y	Z
MOE: 1 per 5-days	2.8	3.1	7.2	20	322	36
POE: 1 per 1-day	2.6	2.6	6.2	53	312	47
DYN: 1 per 12-hours	2.6	2.4	7.6	51	301	44

Note. The POE or 1 per day estimation of along and cross-track OPR accelerations will be assumed in the subsequent estimates of CM

Annual fits to J2 SLR CM estimates (2008.5-2016.0)

-Test SLR bias strategy

-CM estimates are very sensitive to SLR bias strategy

Data	Bias treatment	Amplitude (mm)			Phase (deg)		
		X	Y	Z	X	Y	Z
SLR	nobias	3.5	1.9	8.6	35	282	25
SLR	podbias (ILRS)	3.8	2.4	5.6	42	290	47
SLR	podbias estimated for N. Eq., but suppressed in CM solution *	2.4	1.3	3.4	38	302	47
SLR	allbias (each station/arc)	2.6	2.1	4.6	21	247	26

**** shows even the ILRS bias subset recommended for POD ("podbias") absorbs much of the annual signal in CM***

Annual fits to DORIS CM estimates (2008.5-2012.0)

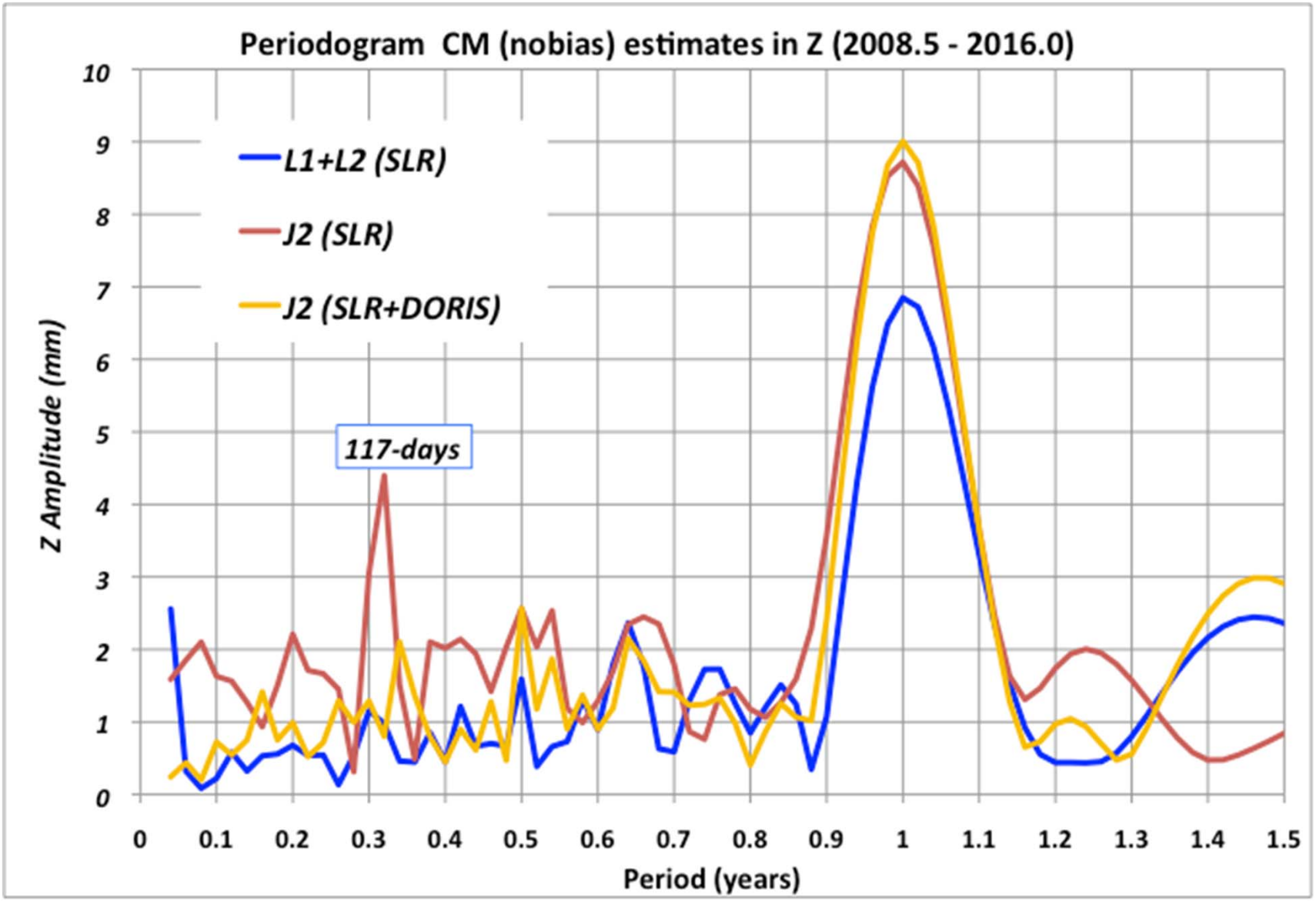
-TEST sensitivity to DORIS measurement & troposphere bias

-CM estimates are sensitive to DORIS bias estimation

Data	Bias treatment	Amplitude (mm)			Phase (deg)		
		X	Y	Z	X	Y	Z
DORIS	ebias	2.3	3.2	10.7	112	333	24
DORIS	bias (explicit passXpass meas & trop per station)	2.0	2.6	10.3	108	348	26
DORIS	biases estimated for Normal Eq., but suppressed in CM solution *	0.7	1.0	8.0	88	345	28

**** shows the required DORIS pass-x-pass bias adjustment will absorb much of the annual signal in CM, although full extent not known***

Periodogram LAGEOS1+2/Jason2 CM estimates in Z: No SLR Biases (2008.5-2016.0)



Annual fits to CM estimates (2008.5-2016.0)

Using similar L1+L2 and Jason2 nobias POD strategies

Annual estimates of CM in Z differ between LAGEOS/Jason2

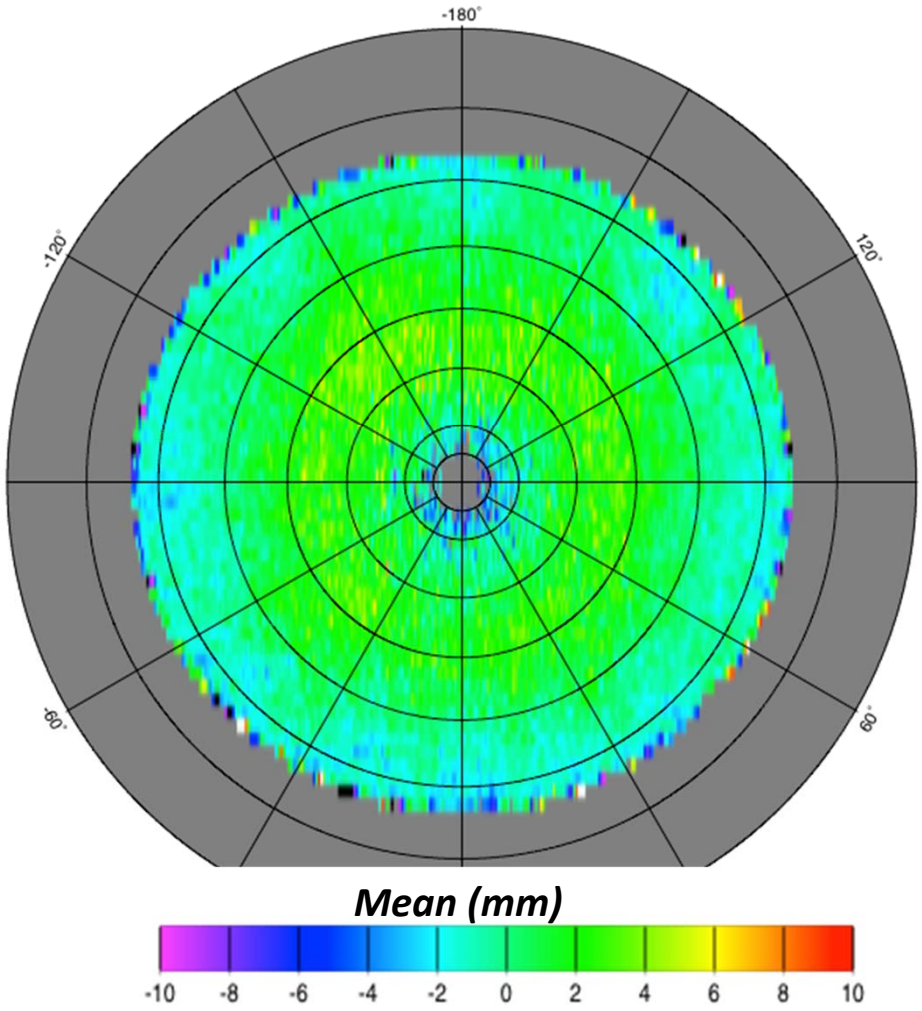
SLR bias treatment	Satellite	Amplitude (mm)			Phase (deg)		
		X	Y	Z	X	Y	Z
nobias	L1+L2	2.8	2.3	6.8	57	305	31
	j2 (slr)	3.4	1.8	8.8	35	284	24
	J2 (slr+dor)	2.6	2.5	9.0	53	307	32

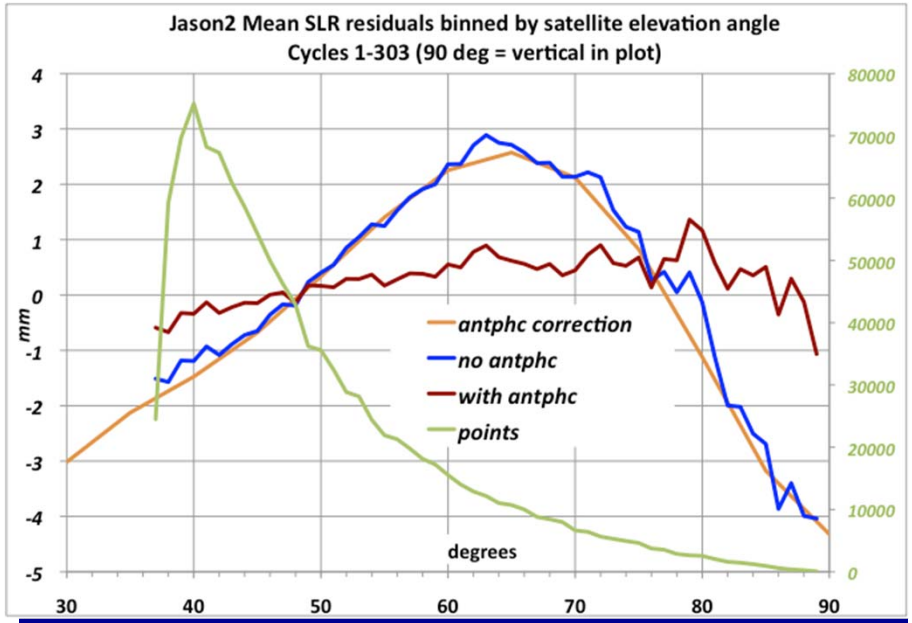
SLR POD Strategy Differences

Model	L1+L2	Jason2
OPR frequency	1 per 7-days	1 per 1-day
elevation cutoff	12 degrees	15 degrees
LRA phase center	(station specific satellite CoM (G. Appleby))	*constant 4.9 cm correction to range*

Jason2 SLR residual map indicates phase center modeling can be improved with satellite elevation angle correction

SLR residuals satellite elevation angle map SLR+DORIS orbits (cycles 1-303)





Mean (& RMS) residuals show LRA phase center modeling <u>IS improved</u> with satellite elevation angle (antphc) correction (mm)

Annual fits to CM estimates (2008.5-2016.0)

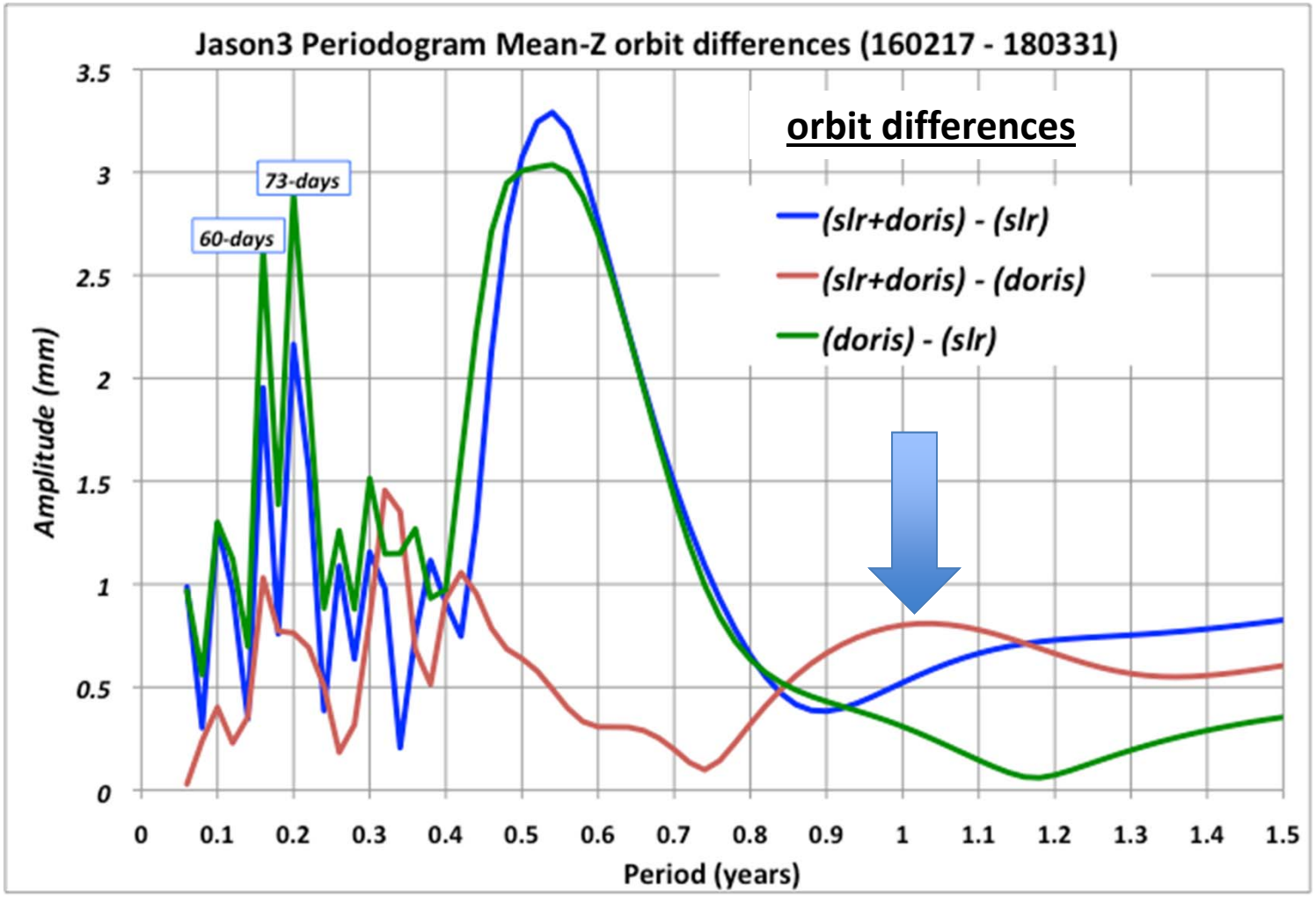
Using Jason2 SLR (poe strategy)

Annual CM estimate IS NOT sensitive to J2 LRA phase center correction (J2/L1L2 difference in CM annual Z-amplitudes remains unexplained)

SLR bias treatment	LRA antphc correction	Amplitude (mm)			Phase (deg)		
		X	Y	Z	X	Y	Z
nobias	no	3.5	1.9	8.6	35	282	25
	yes	3.6	1.9	8.6	34	281	25

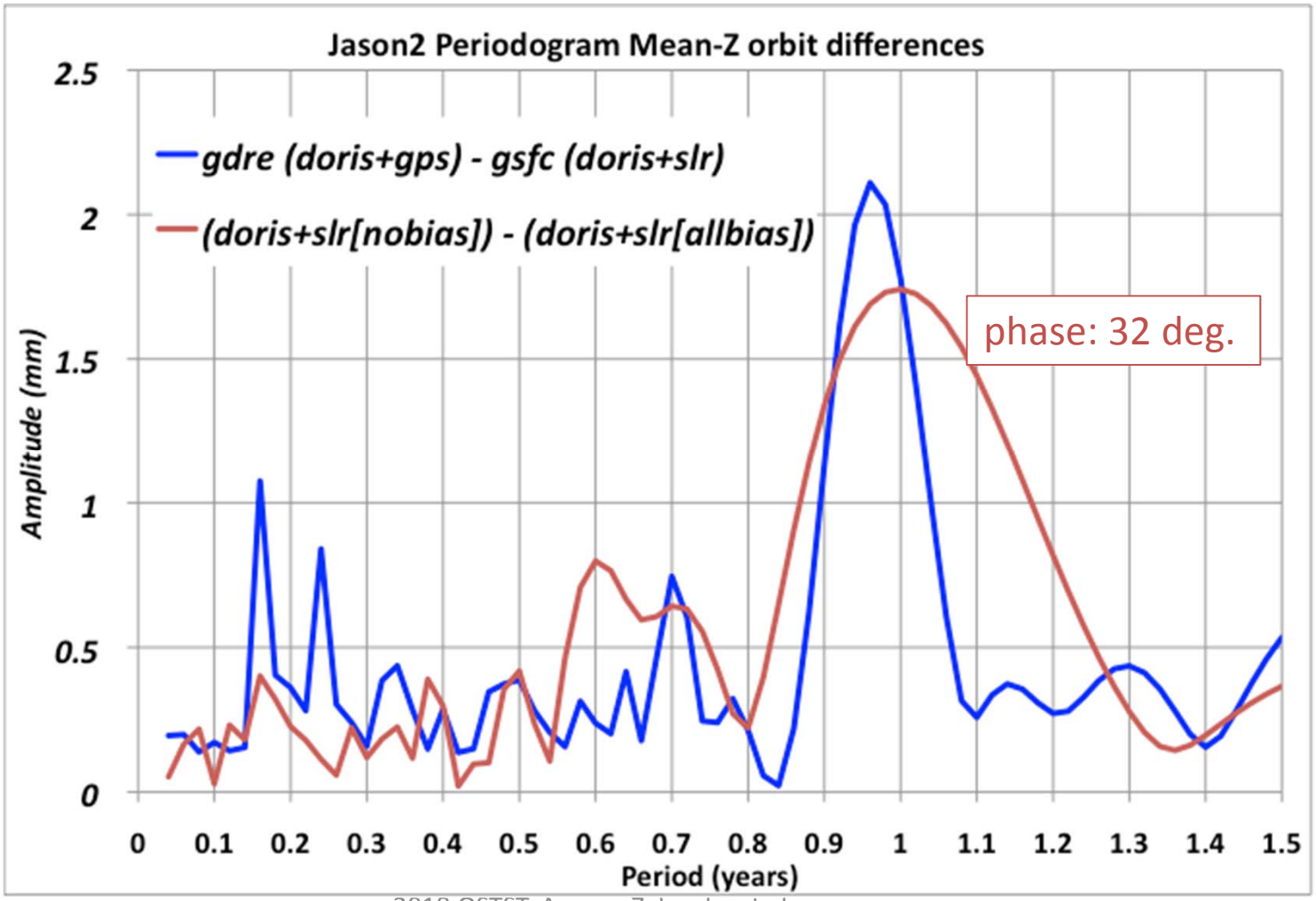
Orbit sensitivity: Will one CM model center SLR/DORIS orbits in the same way?

-YES, annual Z-centering the same for SLR, DORIS, SLR+DORIS orbits (annual Ries (2013) CM model, podbias)



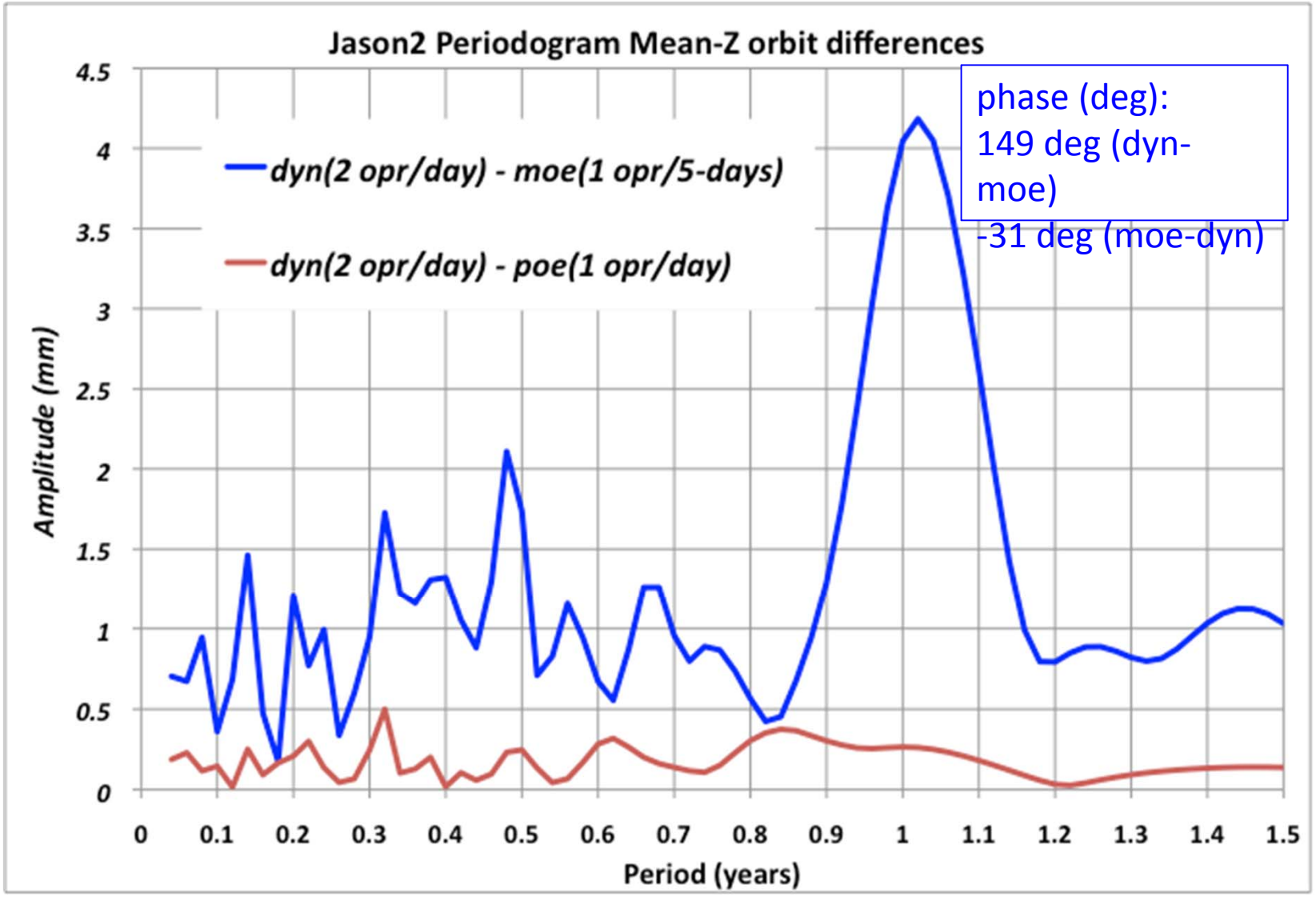
Will one CM model center GDRE/GSFC orbits the same?
-NO, annual Z-centering differs between GDRE/GSFC orbits

Is SLR+DORIS orbit centering sensitive to SLR bias strategy?
-YES



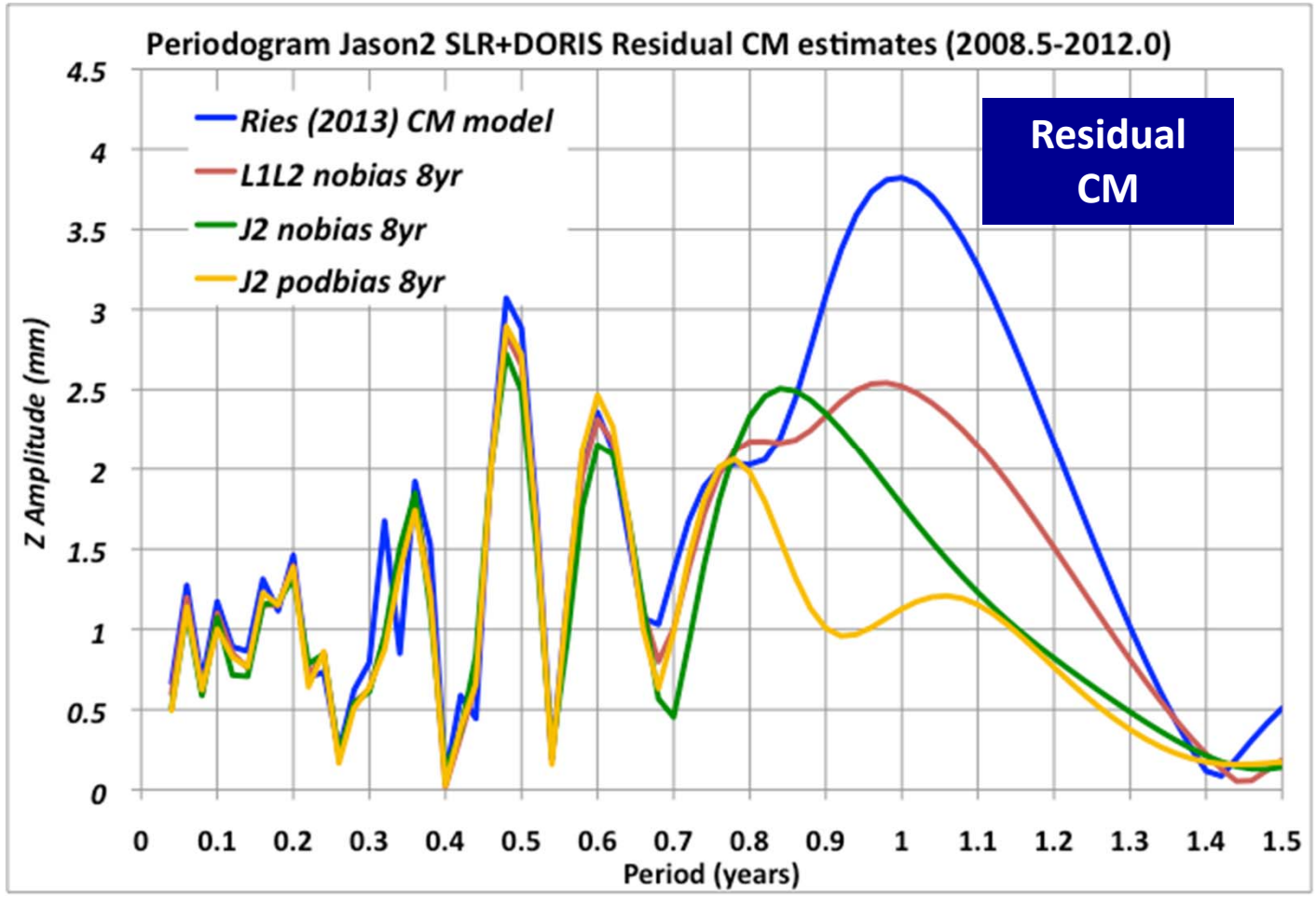
Is SLR+DORIS orbit centering sensitive to empirical acceleration POD strategy?

-YES: annual gravity error signal may confound orbit centering

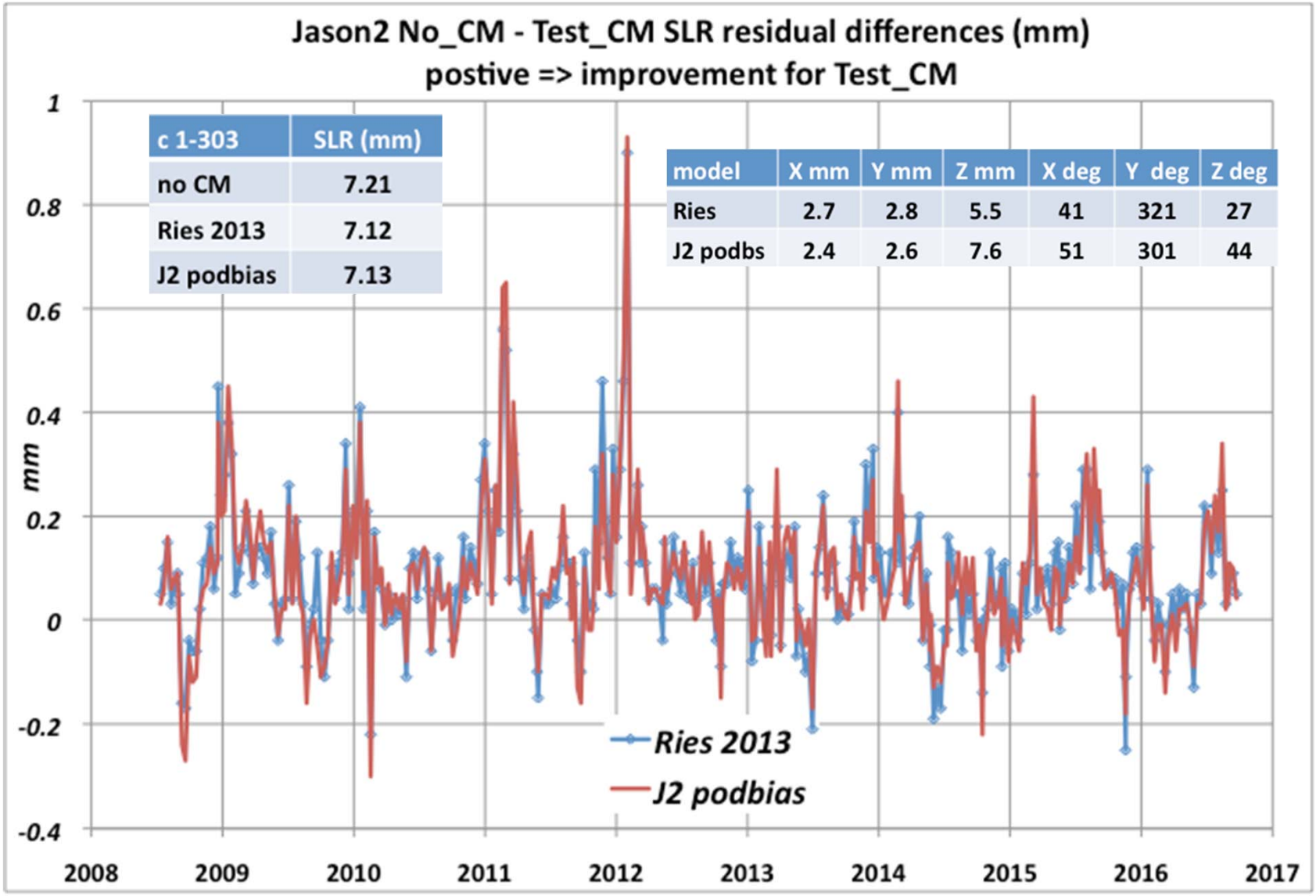


Analysis Question 3
How can we know when the computed orbit origin is best aligned with the Earth's CM?

Although far from perfect, the subject orbit SLR/DORIS sensitivity to geocenter may offer an "objective" test



SLR data can distinguish the presence of a CM model, but does not differentiate between the two Test models



Summary

1) Estimation of SLR/DORIS biases confounds the CM solution, removing much of the annual signal. Bias estimation necessary for DORIS (and GPS) data processing.

1) Annual CM models from LAGEOS1+2 (SLR) and Jason2 (SLR/DORIS) show fair agreement. Reason (s) for differences, especially in Z-amplitudes, remain to be understood.

1) Different orbit solutions may respond differently to the same CM model:
    1) Orbit centering affected by choice of bias and empirical acceleration strategies.
    2) Centering differs between GSFC/CNES orbits using the same CM.

1) The two tests shown of orbit centering accuracy are somewhat limited.

Conclusion and Practical Considerations

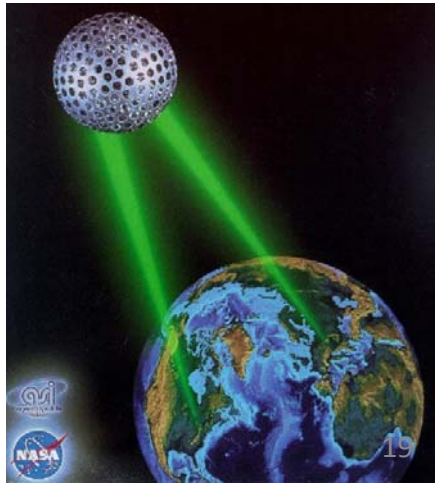
"Realize that everything connects to everything else."
Leonardo da Vinci

1) Rather than making the choice of a single CM model standard, consensus should be reached for the appropriate amplitudes/phases in orbit centering.

1) Differences in J2 SLR/DORIS and J2/L1L2 CM estimates should be understood and requires further study. (error in ITRF?, elevation angle cutoff?, DORIS troposphere error? ….??)

1) Developing objective tests of accuracy in alignment of the orbit origin with CM (if possible) seems important and should be pursued. Impact on altimeter data analysis?

Thank you



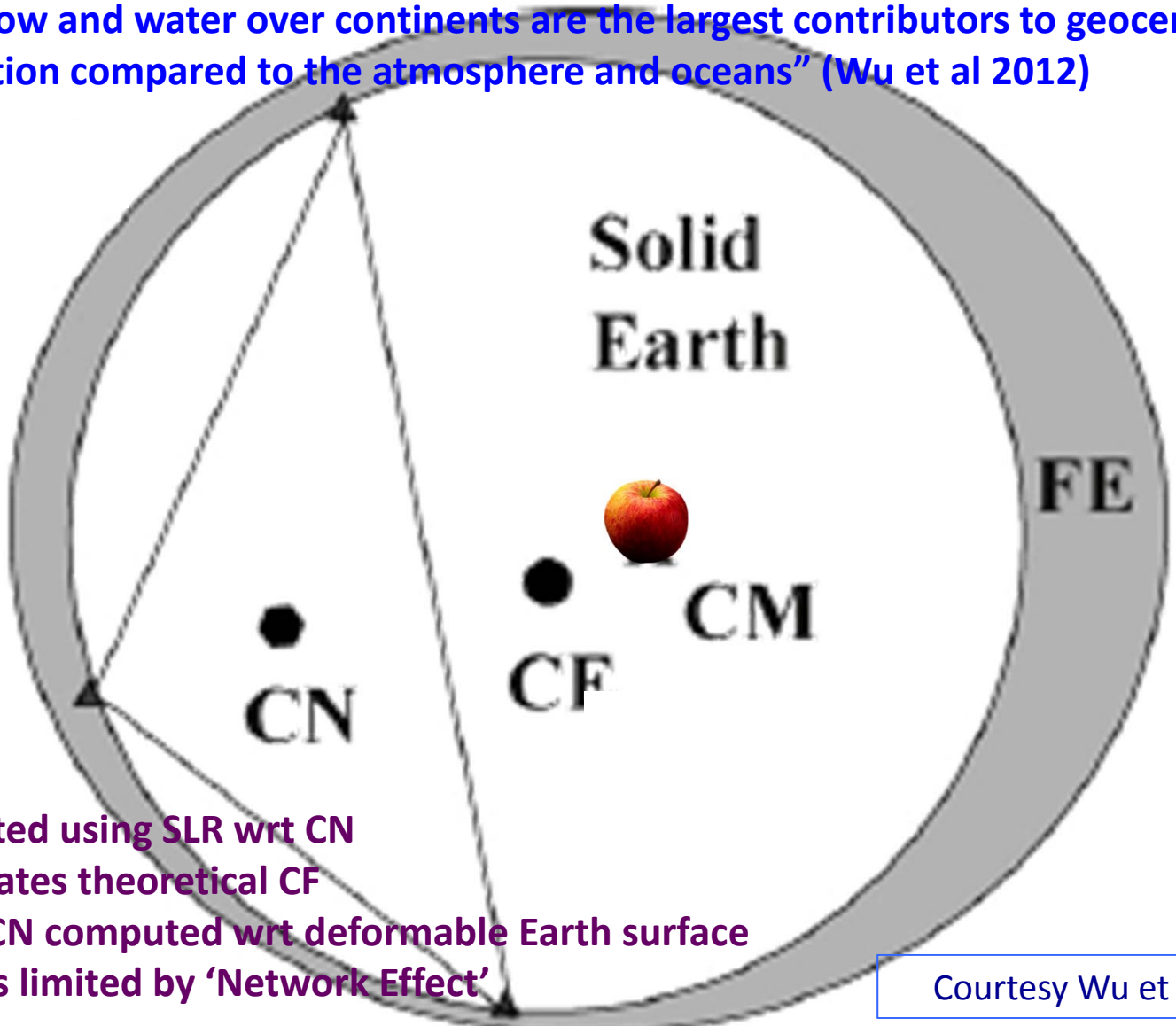

BACKUP

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

GEODYN nuisance bias (ebias) definition

Nuisance biases are partitioned from other estimated parameters so they only contribute to correct the data in the pass and do not enter into the complete solution. So for example the estimation of these parameters will not influence the estimation of any other parameters, such as the orbit state.

Where $$\delta m = B_e \Delta b + B \Delta x + \varepsilon \quad (1)$$

$\boldsymbol{\delta m}$ = *the vector of residuals* $(O - C)$

$\boldsymbol{\Delta b}$ = *the set of corrections that should be made to the electronic biases*

$\boldsymbol{B_e}$ = the matrix of partial derivatives of the measurements with respect to the biases. The elements of this matrix are either 1's or 0's

$\boldsymbol{\Delta x}$ = *the set of corrections to be made to all other adjustable parameters*

$\boldsymbol{B}$ = the matrix of partial derivatives of the measurements with respect to the $\boldsymbol{x}$ parameters

$\boldsymbol{\varepsilon}$ = *the measurement noise vector*

The least squares solution of (1) is:

$$\begin{bmatrix} \Delta\hat{b} \\ \Delta\hat{x} \end{bmatrix} = \begin{bmatrix} B_e^T W B_e & B_e^T W B \\ B^T W B_e & B^T W B \end{bmatrix}^{-1} \begin{bmatrix} B_e^T W \delta m \\ B^T N \delta m \end{bmatrix}$$

GSFC annual CM model using ILRS-based bias strategy in good agreement with other recent L1+L2 SLR-based models

Recent SLR CM solutions	Amplitude (mm)			Phase (degrees)		
	X	Y	Z	X	Y	Z
GSFC (2017) 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

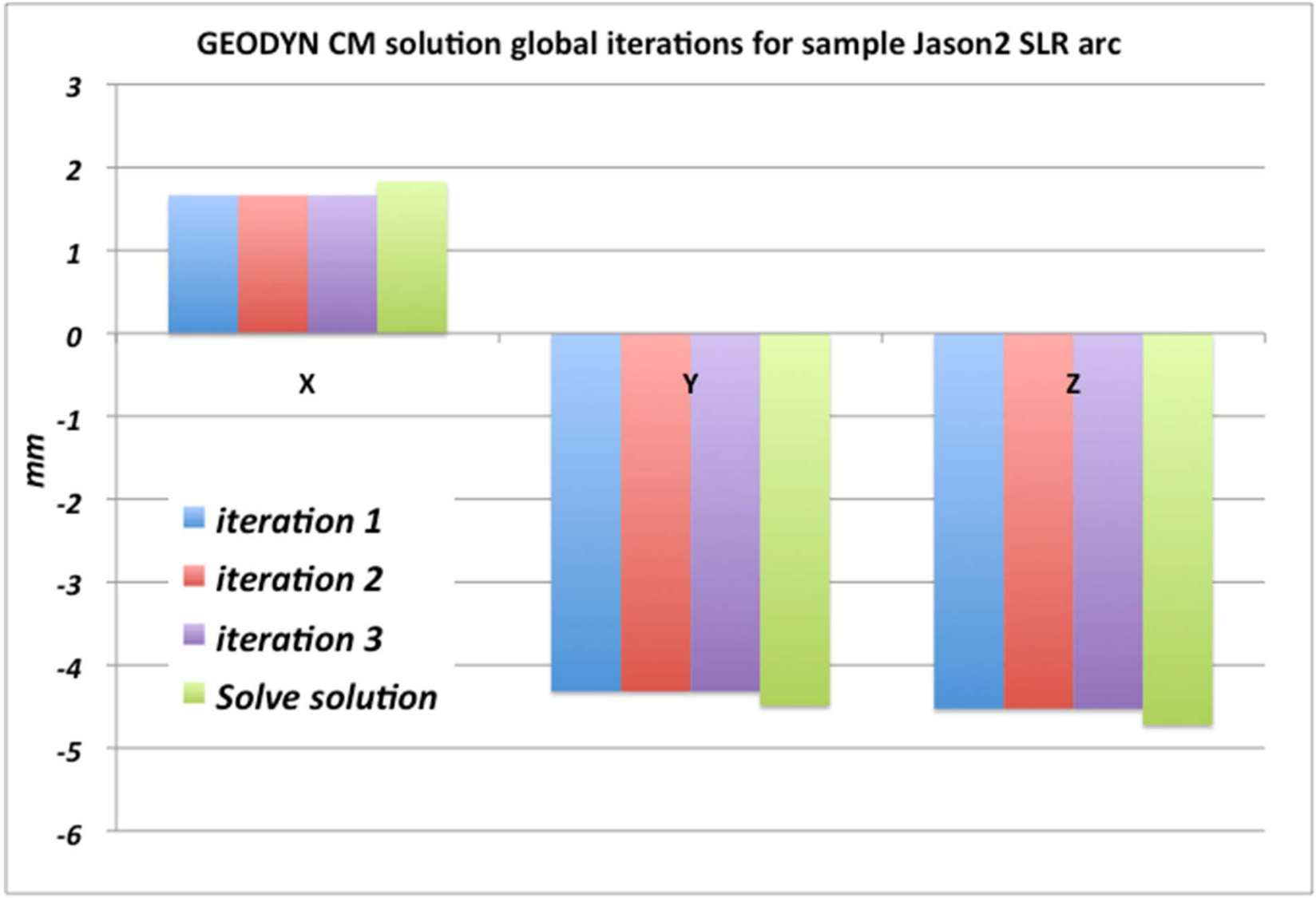
→ ***Ergo, we process SLR data in about the same way***

GSFC annual L1+L2 SLR-based CM models with Atmosphere Pressure Loading shows better agreement with non-SLR models which already account for non-tidal Loading

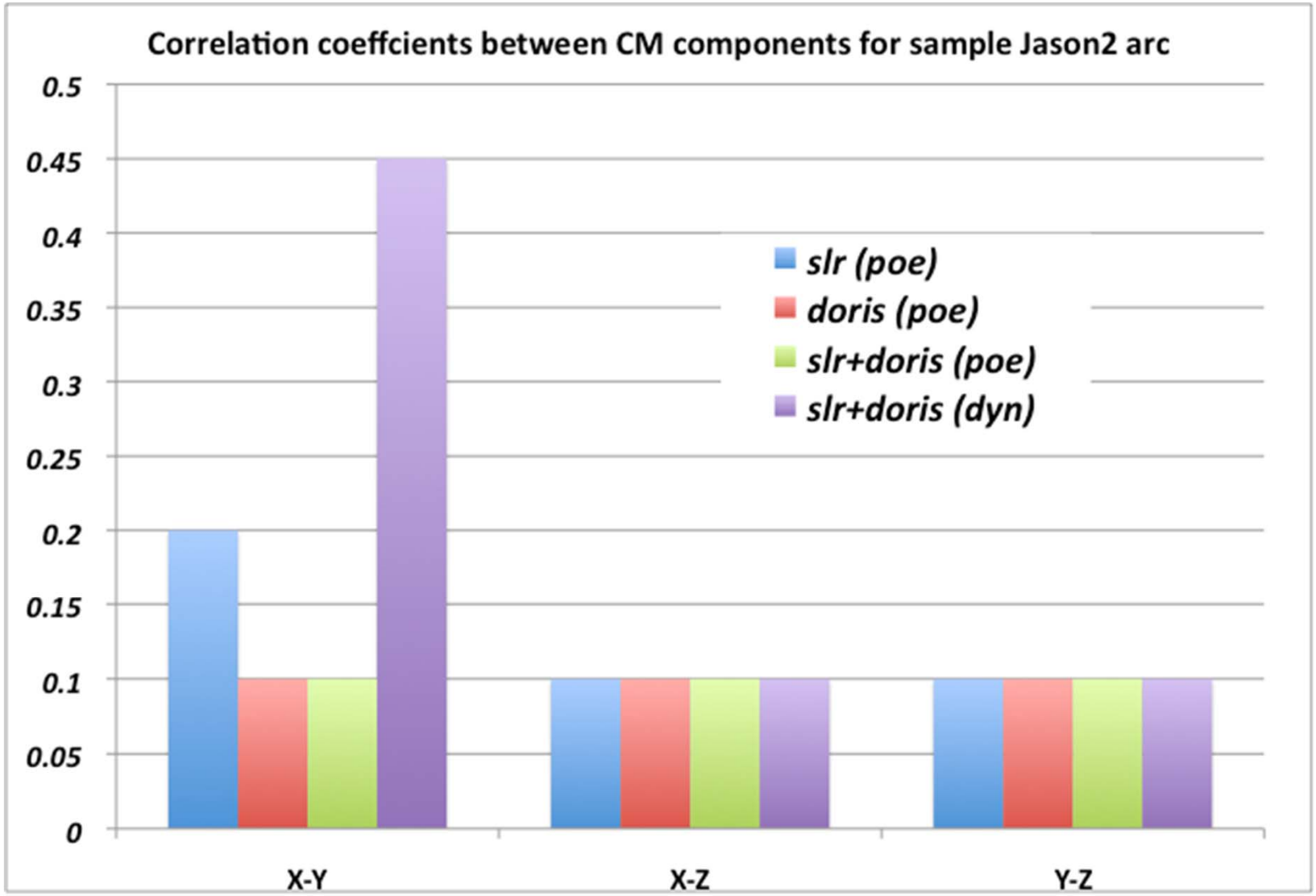
Recent CM solutions	Amplitude (mm)			Phase (degrees)		
	X	Y	Z	X	Y	Z
GSFC L1+L2, ILRS-bias, no APL	2.3	2.6	6.2	48	319	33
GSFC L1+L2, No bias, APL	2.6	1.9	4.6	67	294	49
GSFC L1+L2, ILRS-bias, APL	1.9	1.9	4.2	70	301	54
GPS loading+ GRACE+ OBP (Wu etal, 2012)	1.8	2.7	4.2	54	321	21
GRACE + Ocean model (Swenson etal 2008 (updated 2012)) (Ries 2016)	2.2	3.0	2.7	43	333	42

However, our interest is not to achieve further improved agreement via POD strategy, but - to understand the sensitivity of the CM estimate & orbit centering to POD strategy

Validation / Sanity-Check for using the GEODYN-SOLVE combination for estimation of CM (sample J2 SLR arc 080712)



Sample SOLVE CM solution correlation coefficients for 10-day arc (J2 SLR arc 080721)

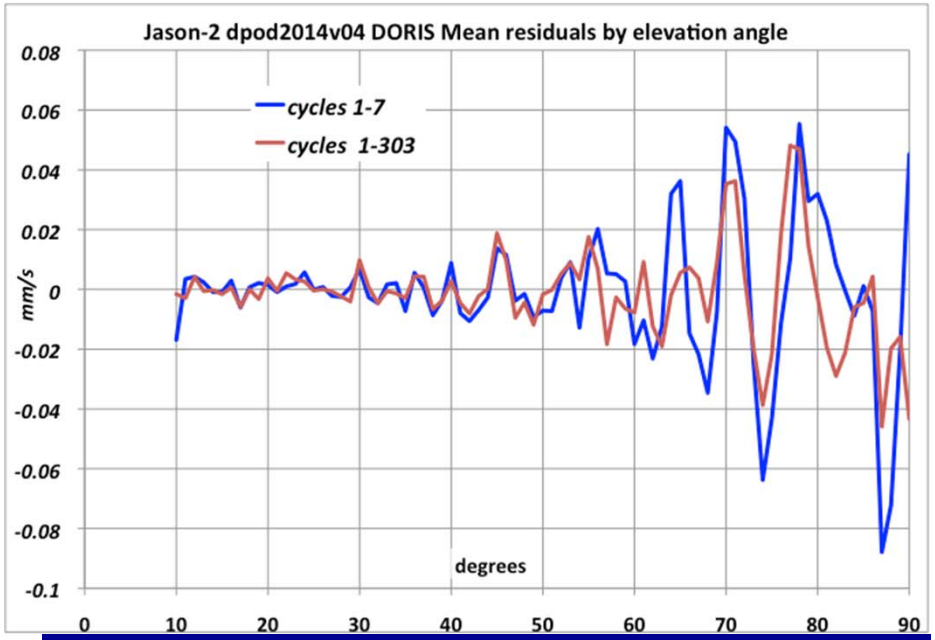


Annual fits to CM estimates (2008.5-2016.0)
using Jason-2 SLR (poe processing)
-Evaluate SOLVE processing

-nobias and podbias (suppress, shift) solutions are very similar, but which ideally should be the same

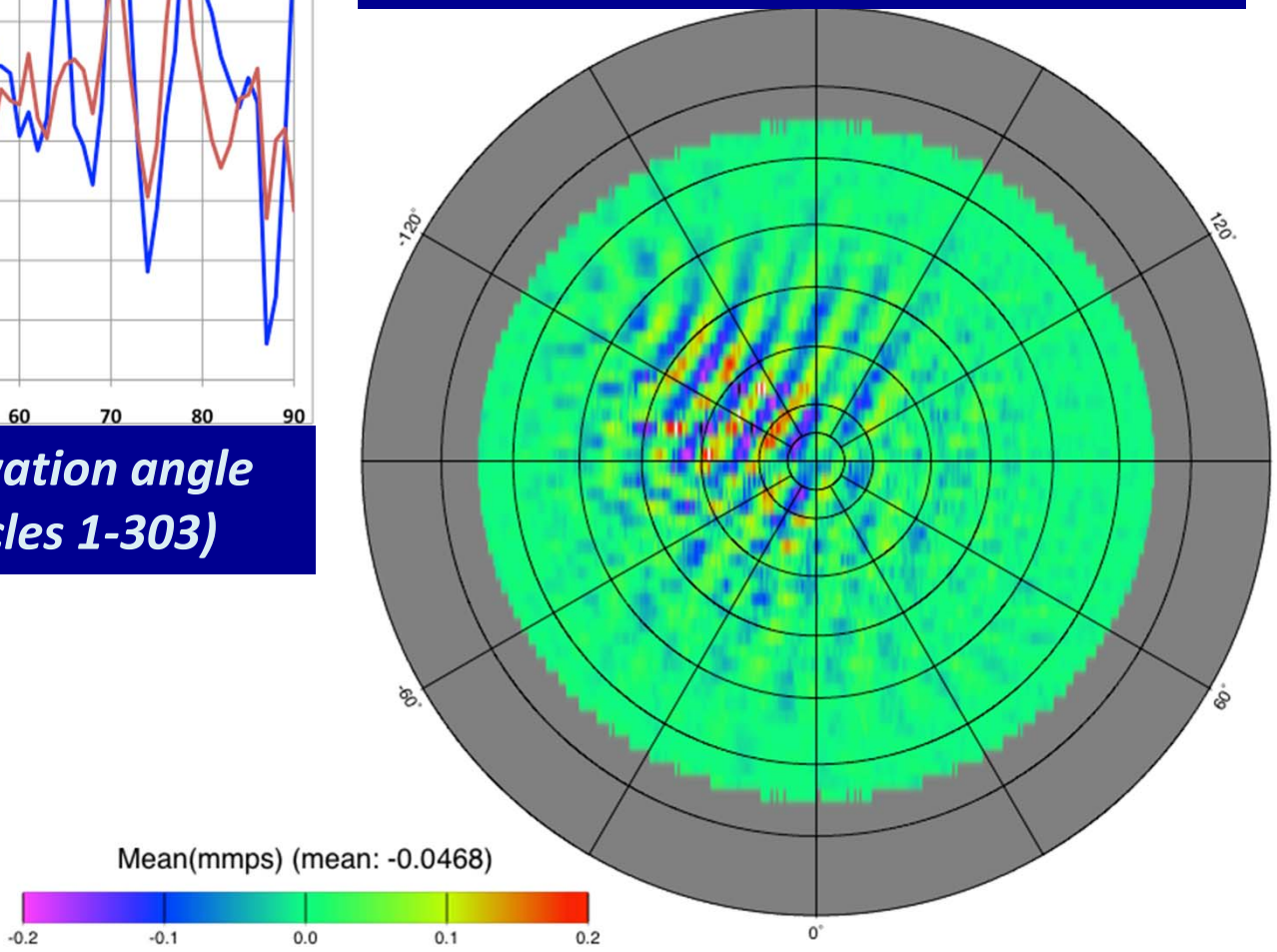
Data	Bias treatment	Amplitude (mm)			Phase (deg)		
		X	Y	Z	X	Y	Z
SLR	nobias (no biases in POD)	3.5	1.9	8.6	35	282	25
SLR	podbias (ILRS) biases estimated for N.E., and simultaneously estimated in SOLVE CM solution	3.8	2.4	5.6	42	290	47
SLR	podbias estimated for N.E. , but biases shifted->0 and suppressed in SOLVE CM solution	3.1	1.8	9.7	43	282	21

Jason2 Mean DORIS residuals suggest multipath effect for satellite antenna (mm/s)



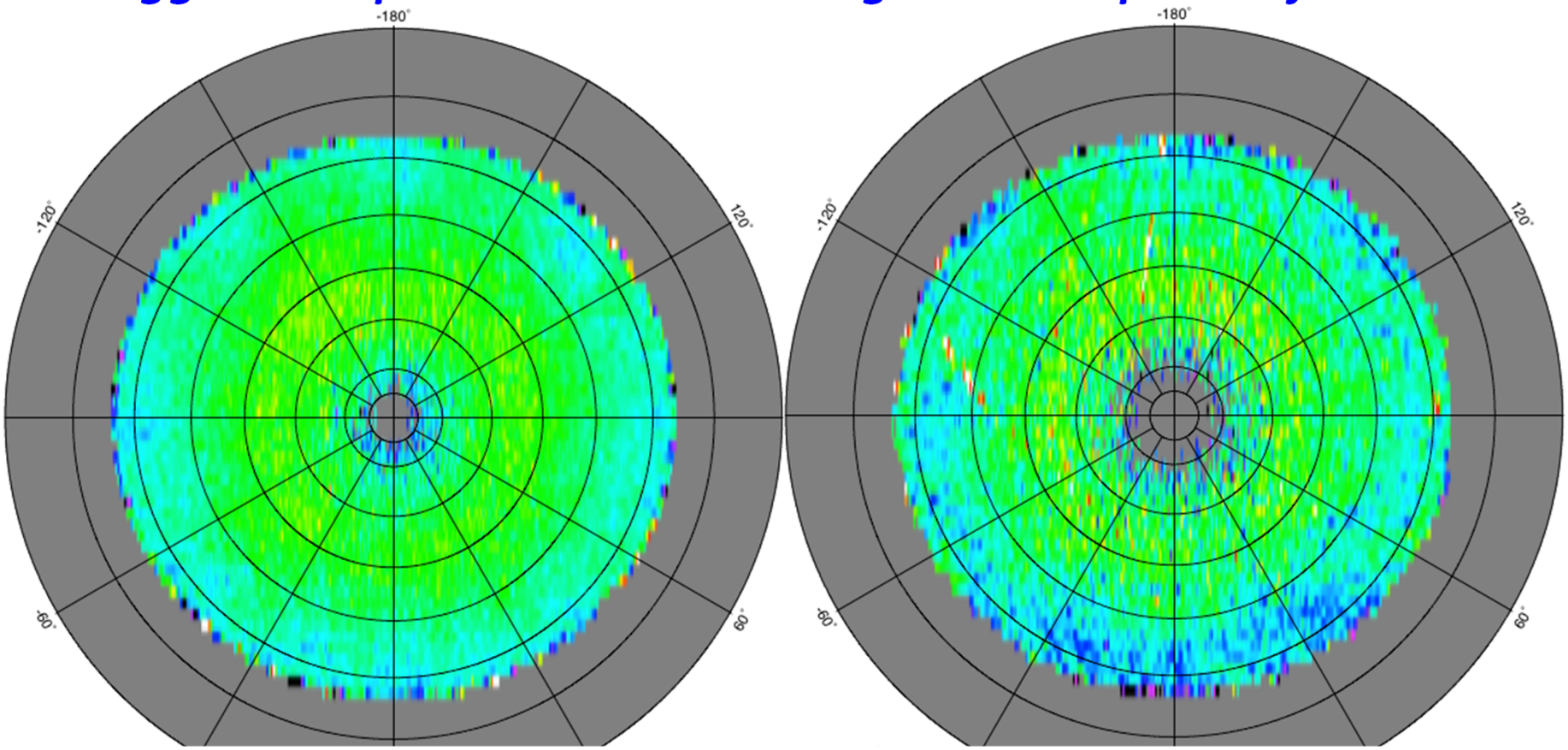
DORIS residuals by elevation angle SLR+DORIS orbits (cycles 1-303)

DORIS residuals by satellite elevation angle jpl17a orbits (cycles 1-303)



Satellite azimuth-elevation maps of SLR residuals (mm)
GSFC (SLR+DORIS) orbits

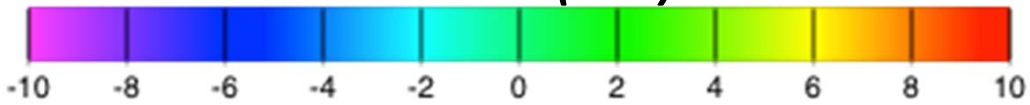
suggest LRA phase center modeling can be improved for J2 & J3



Jason2 (cycles 1-303)

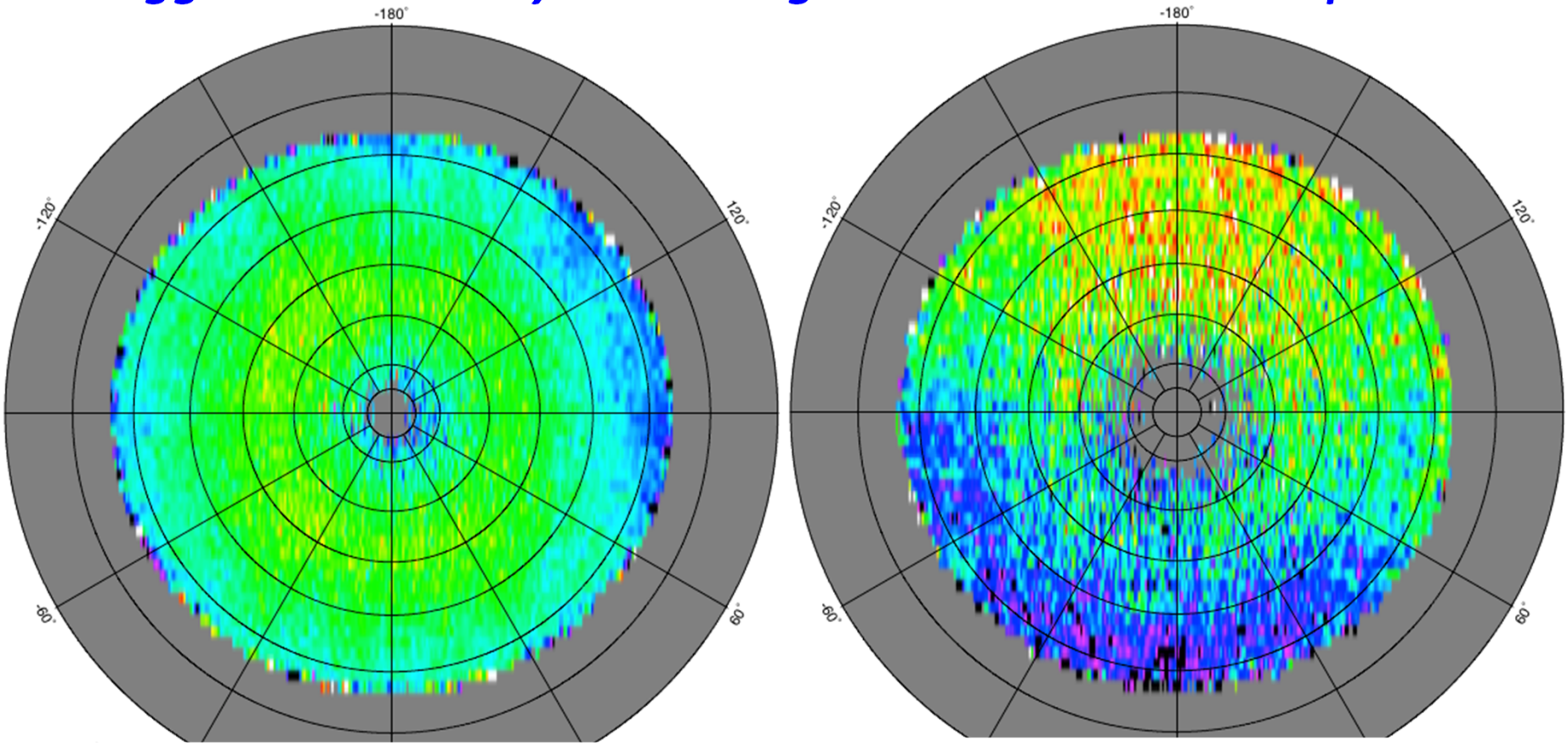
Jason3 (cycles 1-092)

Mean (mm)



Satellite azimuth-elevation maps of SLR residuals (mm)
GDRE (GPS+DORIS) orbits

suggests J3 LRA may be mis-aligned with GPS antenna position



Jason2 (cycles 1-303)

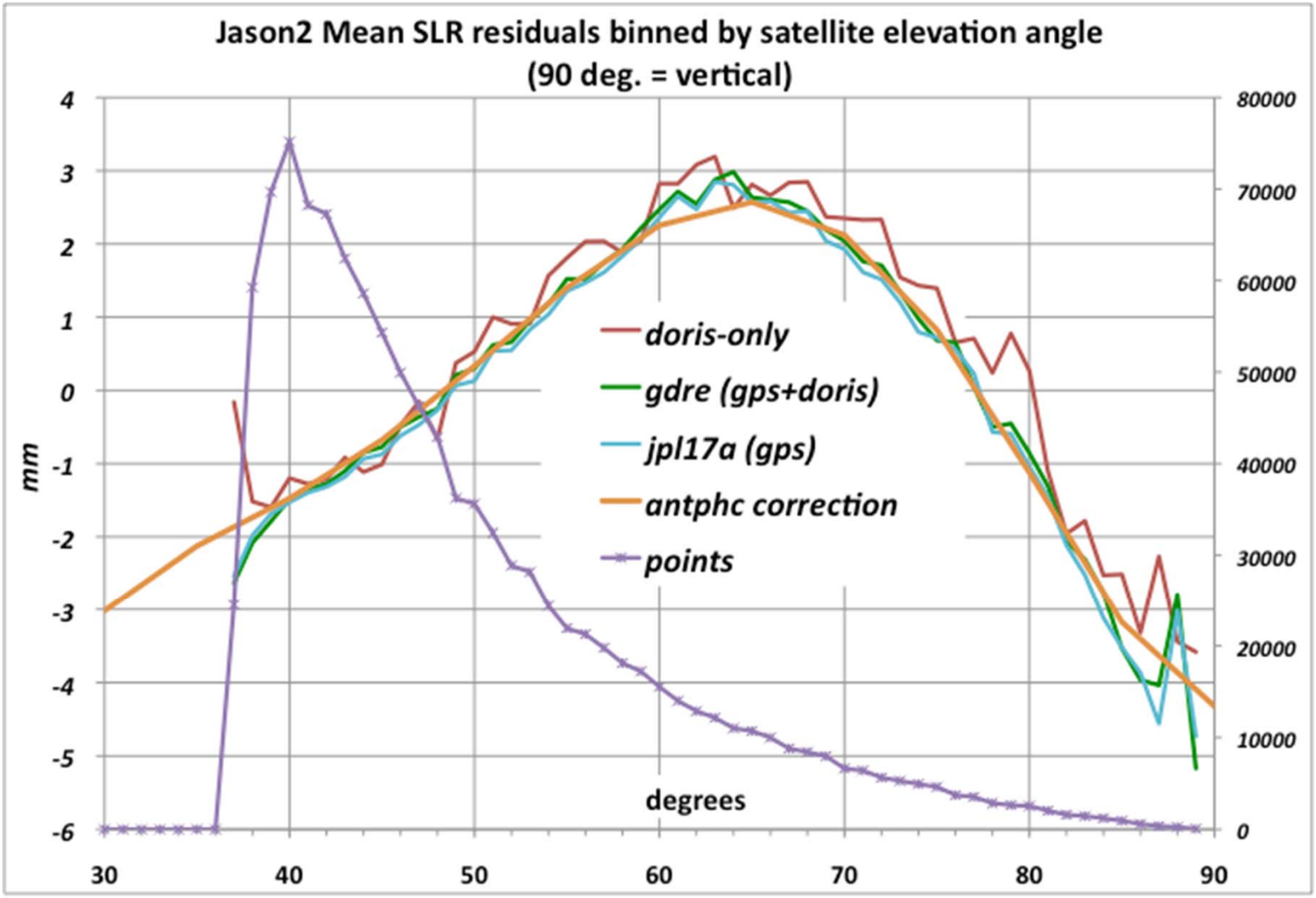
Jason3 (cycles 1-070)

Mean (mm)

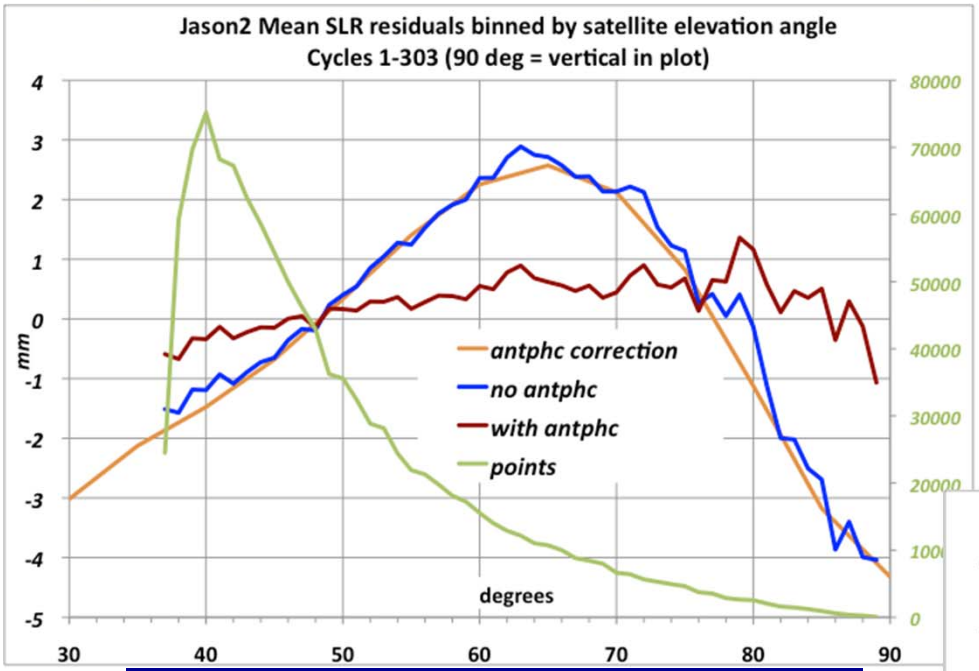
-10 -8 -6 -4 -2 0 2 4 6 8 10

Jason2 Mean SLR Residuals from GPS/DORIS orbits (2008.5-2016.0)

LRA phase center correction from Mean Residuals (antphc)

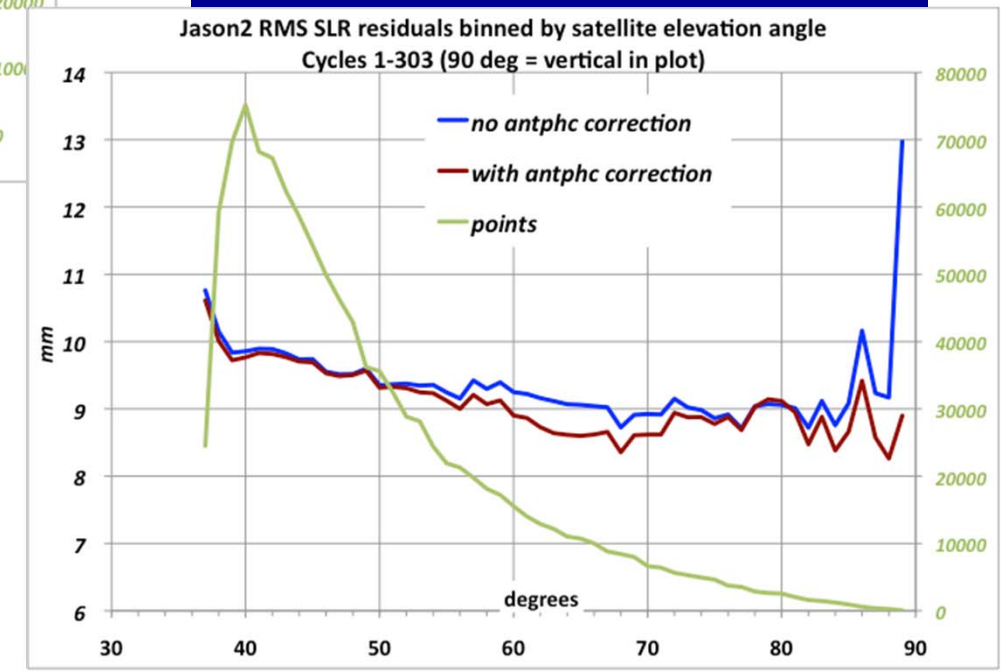


Jason2 LRA phase center modeling improved with satellite elevation angle antphc correction (SLR+DORIS POD)

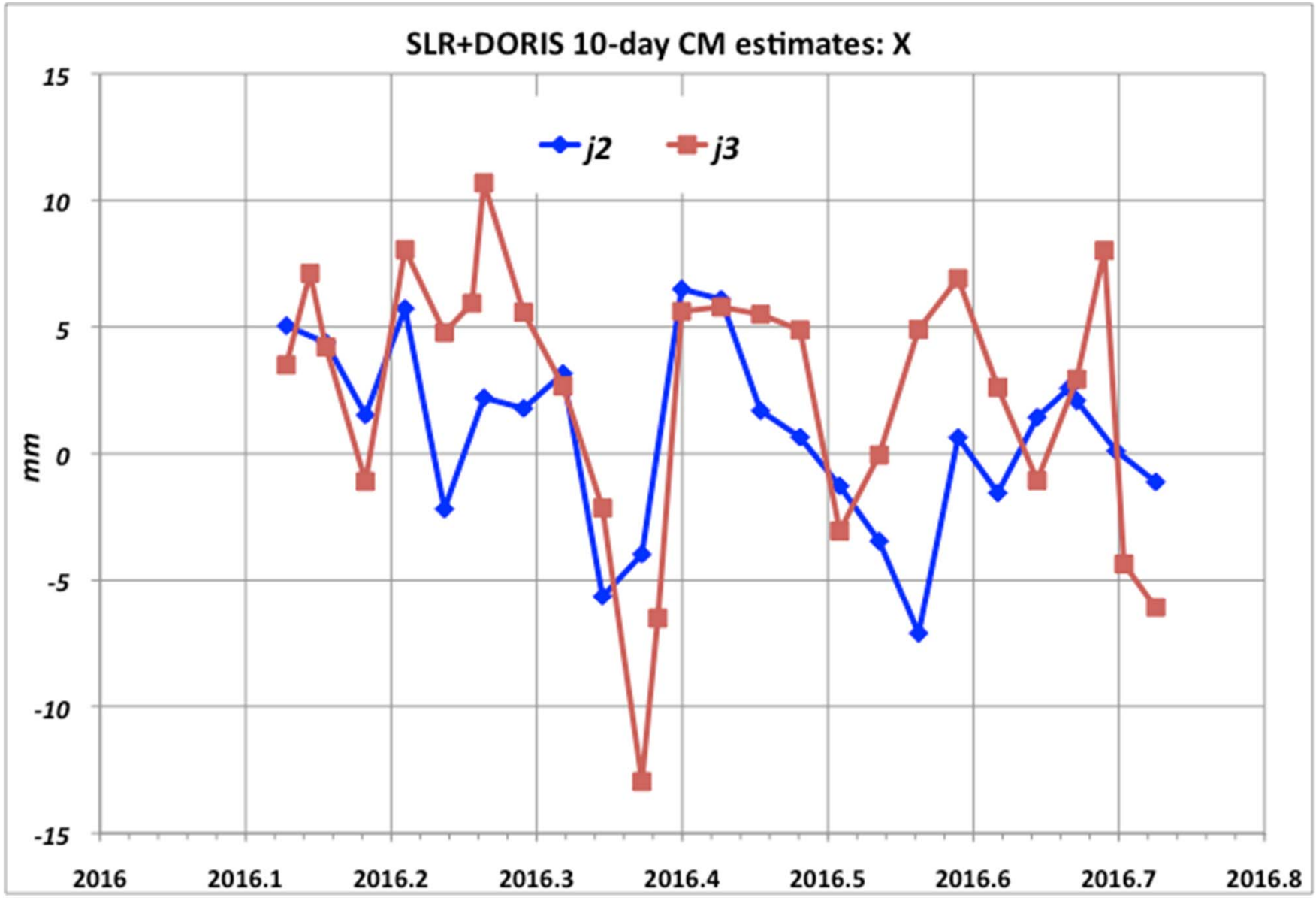


Jason2 Mean SLR residuals (mm) by satellite elevation angle

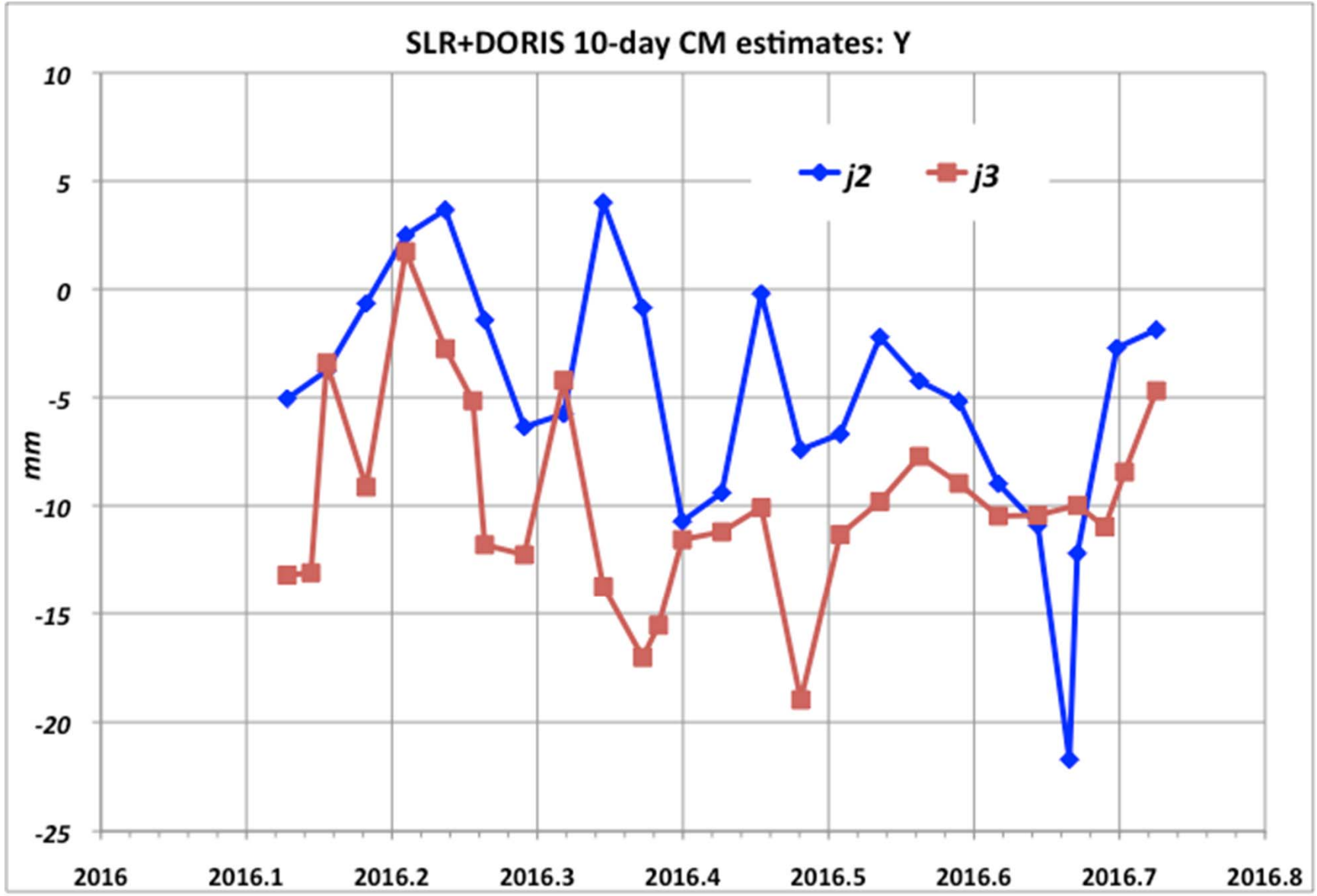
Jason2 RMS SLR residuals (mm) by satellite elevation angle



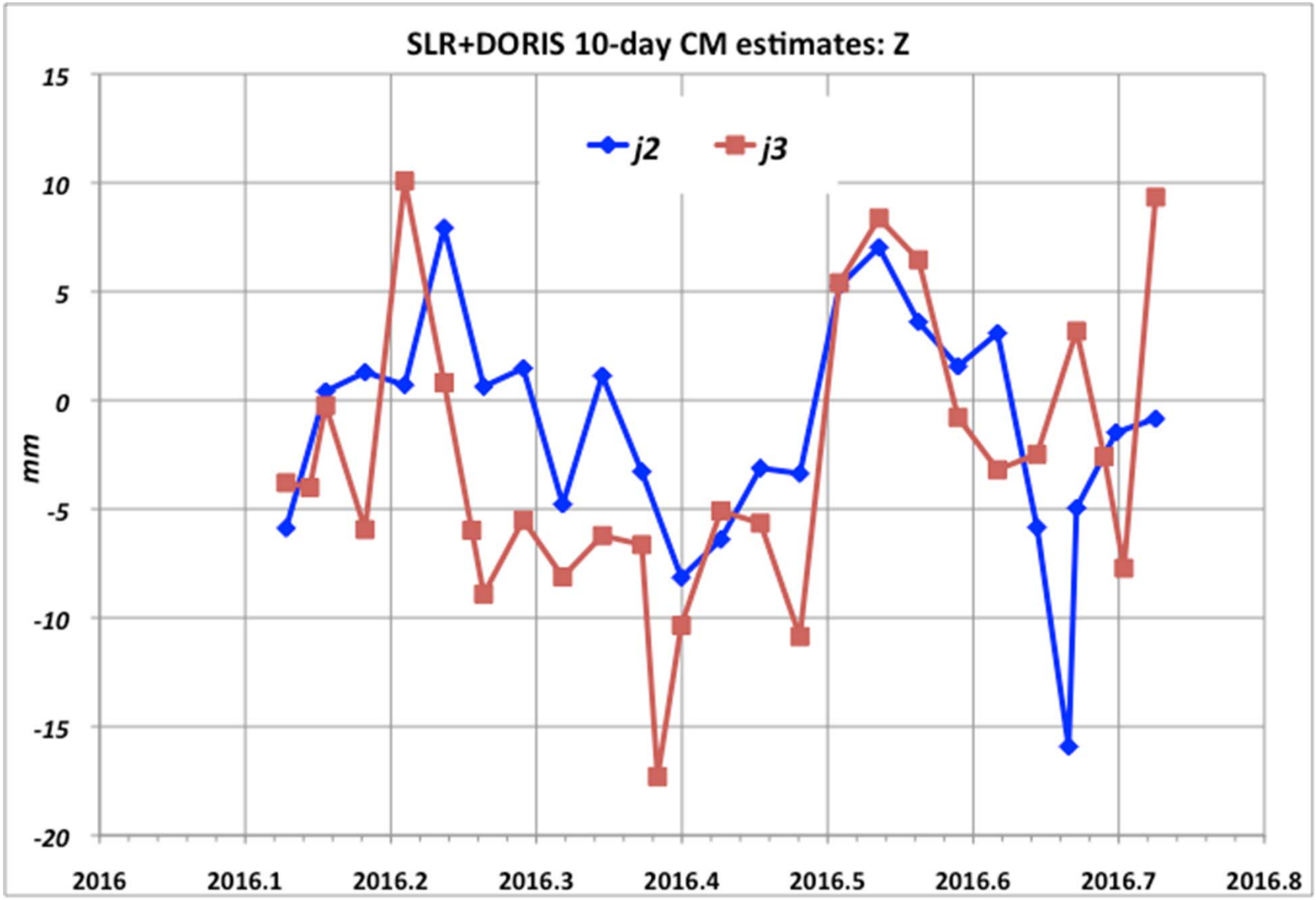
Jason-2/3 SLR+DORIS CM 10-day estimates in X



Jason-2/3 SLR+DORIS CM 10-day estimates in Y



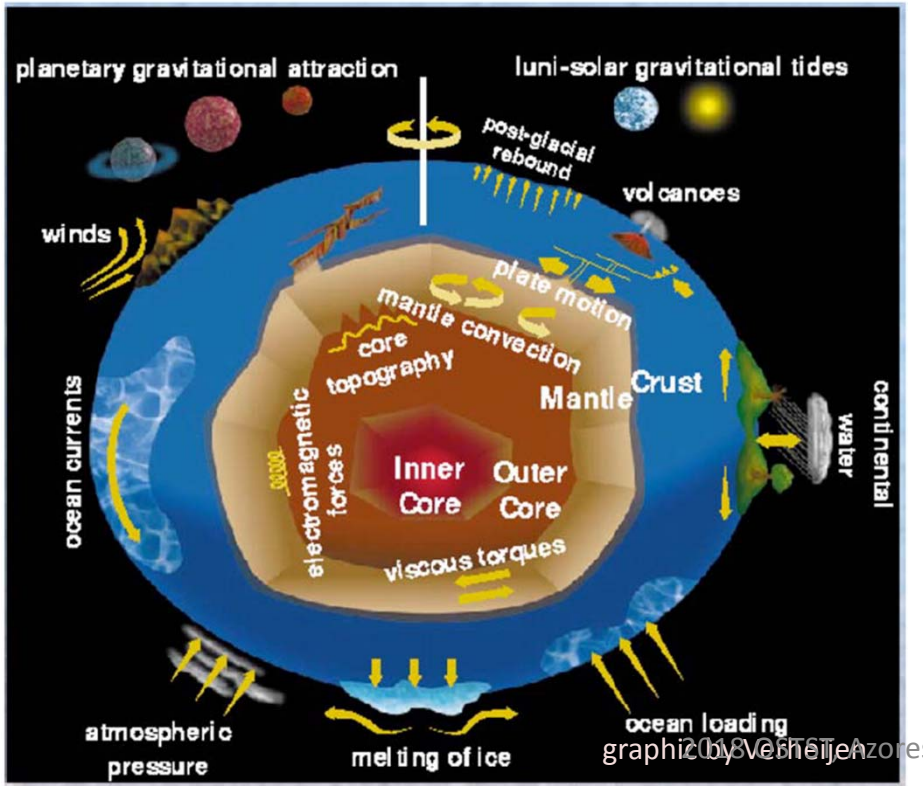
Jason-2/3 SLR+DORIS CM 10-day estimates in Z



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:

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



graphic by Vermeer

$r_{cm}(t)$: 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.

Conclusions (2017 OSTST)

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