Reconciling Estimates of Annual Geocenter Motion from Space Geodesy

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Geocenter Motion and Mass Redistribution

- By definition, the ITRF does not include variations between the mean and instantaneous center of mass; these must be included as a correction
- IERS conventions include tidally coherent geocenter motion, but not non-tidal; non-tidal variations dominate the annual geocenter motion.
- An estimate of the annual geocenter motion is essential:
  - Represents the largest scale mass redistribution on Earth, but it is not captured in GRACE estimates

$$\vec{r}_{cm} = a_e \sqrt{3}(\bar{C}_{11}, \bar{S}_{11}, \bar{C}_{10})$$

Effects of 1 mm Geocenter Motion
On GRACE Mass Change estimates

Region	GX	GY	GZ
Non-Steric Global Mean Sea Level	- 0.46 mm	- 0.26 mm	- 0.51 mm
Antarctica Mass Change	0.5 Gt	5 Gt	- 69 Gt

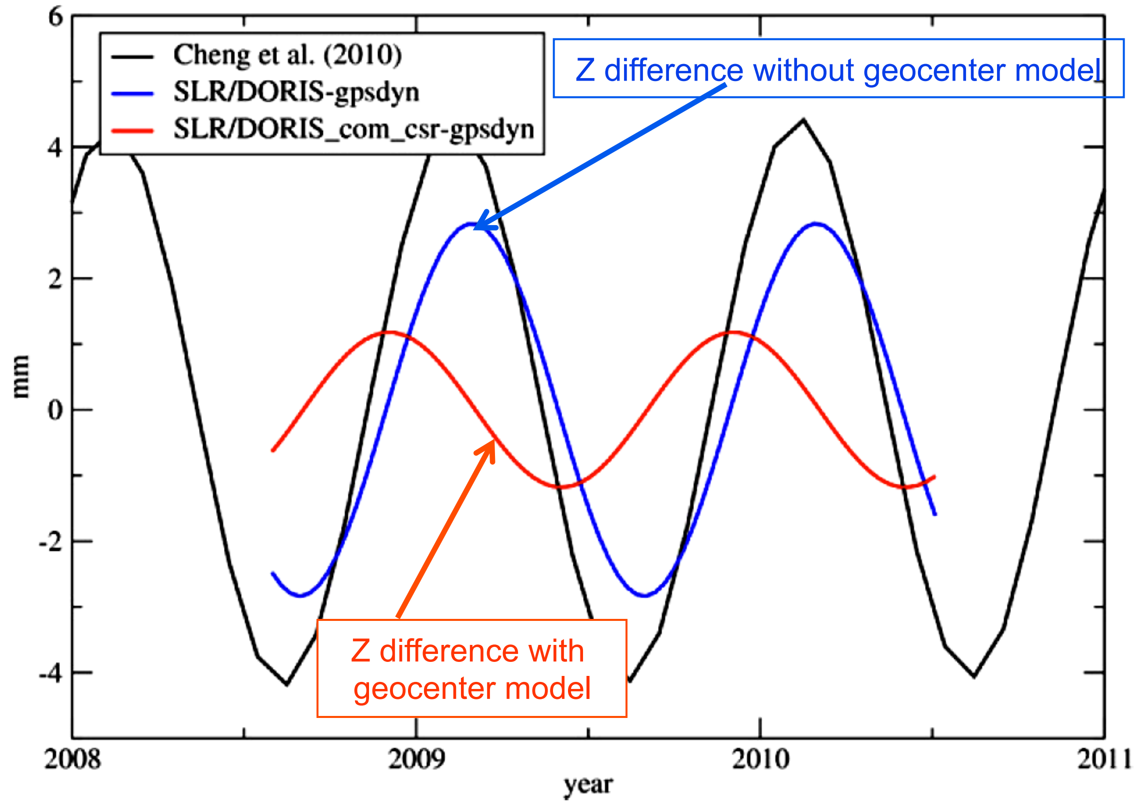
from Wu & Heflin, 2014

Geocenter Motion and Orbit Determination (1)

Failure to account for annual geocenter motion in orbit determination can cause false signals in geodetic products, such as sea surface height estimates from space altimeters

Jason-2 orbit comparisons between GPS-based and SLR-DORIS-based orbits exhibit seasonal variation in Z

Adding geocenter motion model reduces systematic difference (Melachroinos et al., 2013)

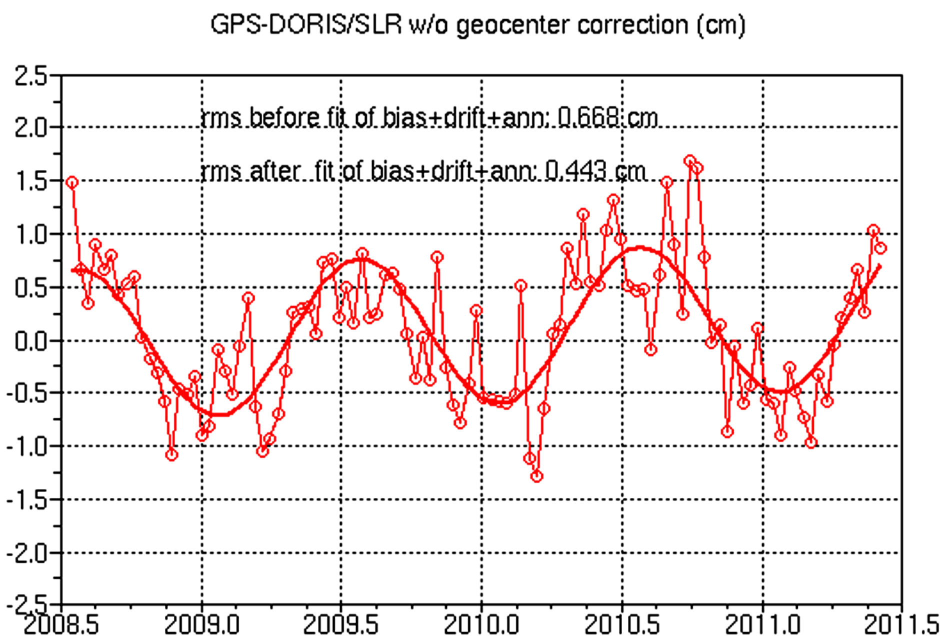


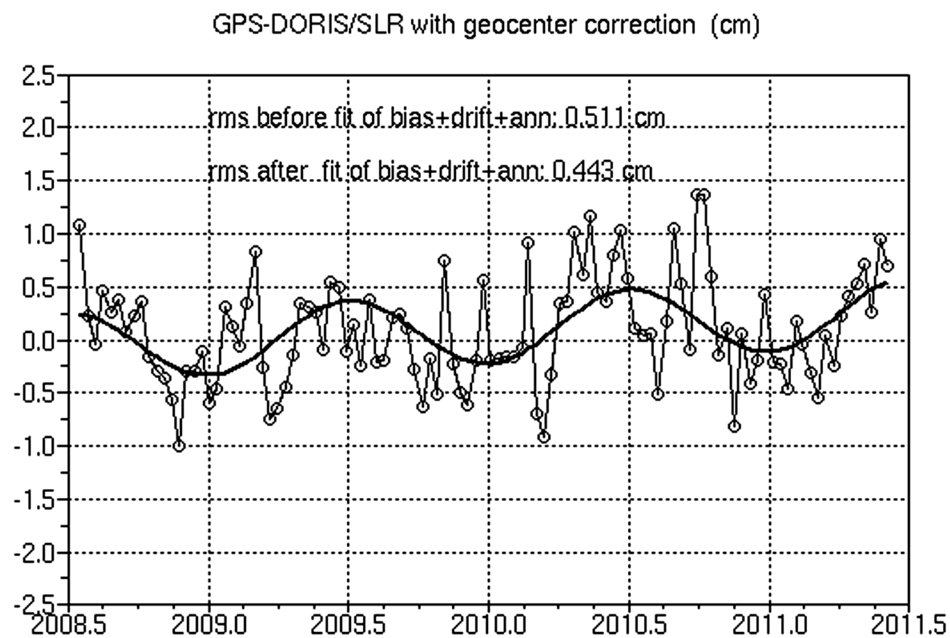
Geocenter Motion and Orbit Determination (2)

Jason-2 orbit comparisons between GPS-based and SLR-DORIS orbits exhibit seasonal variation in Z that are reduced with a model (Cerri, 2011, personal communication)

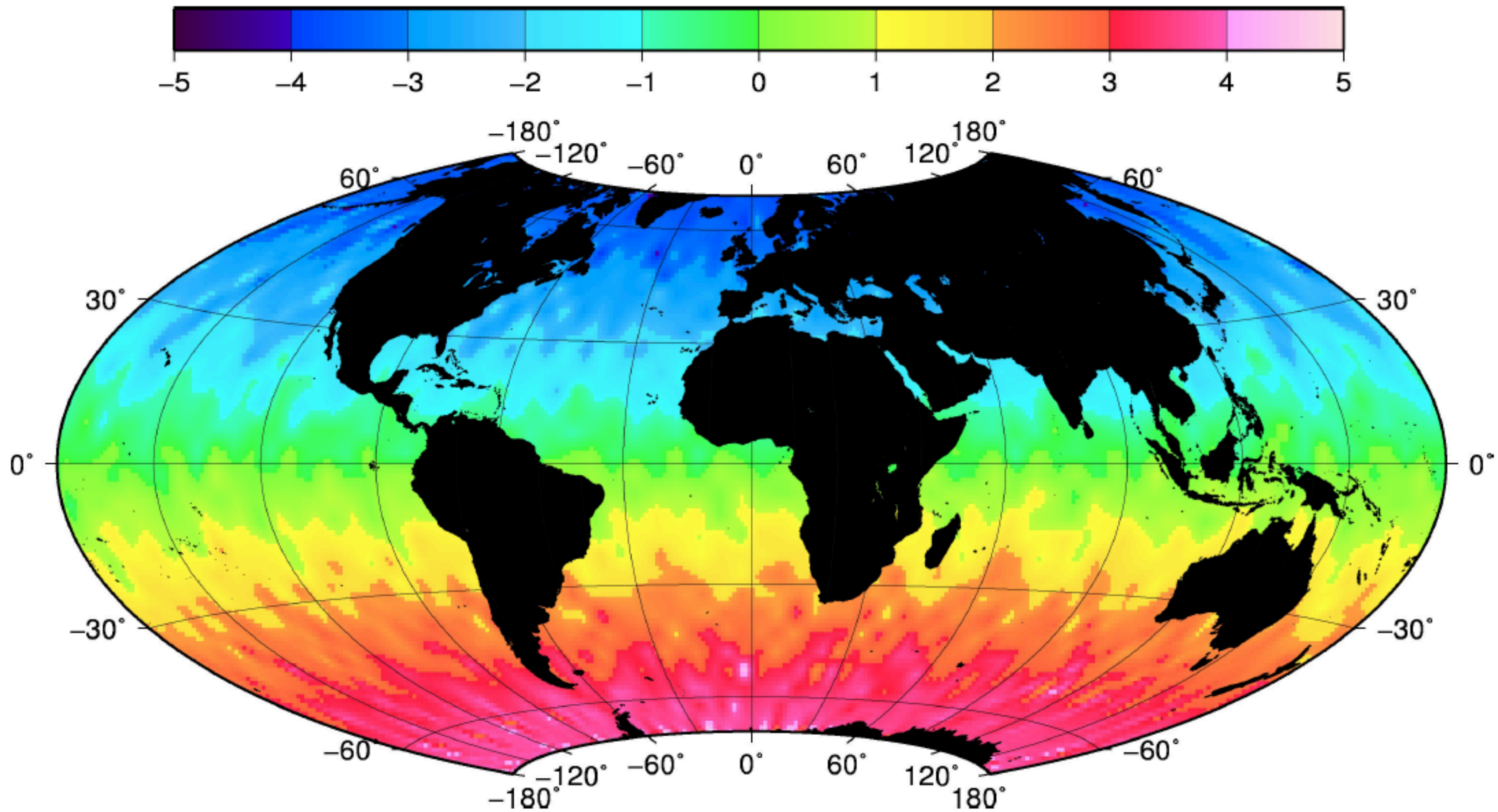
Cerri used 4.2 mm for annual Z; more recent SLR estimates suggest something closer to 5-6 mm, which looks like it would have reduced the differences further

We should expect to get consistent orbits regardless of technique; geocenter motion model is essential for this





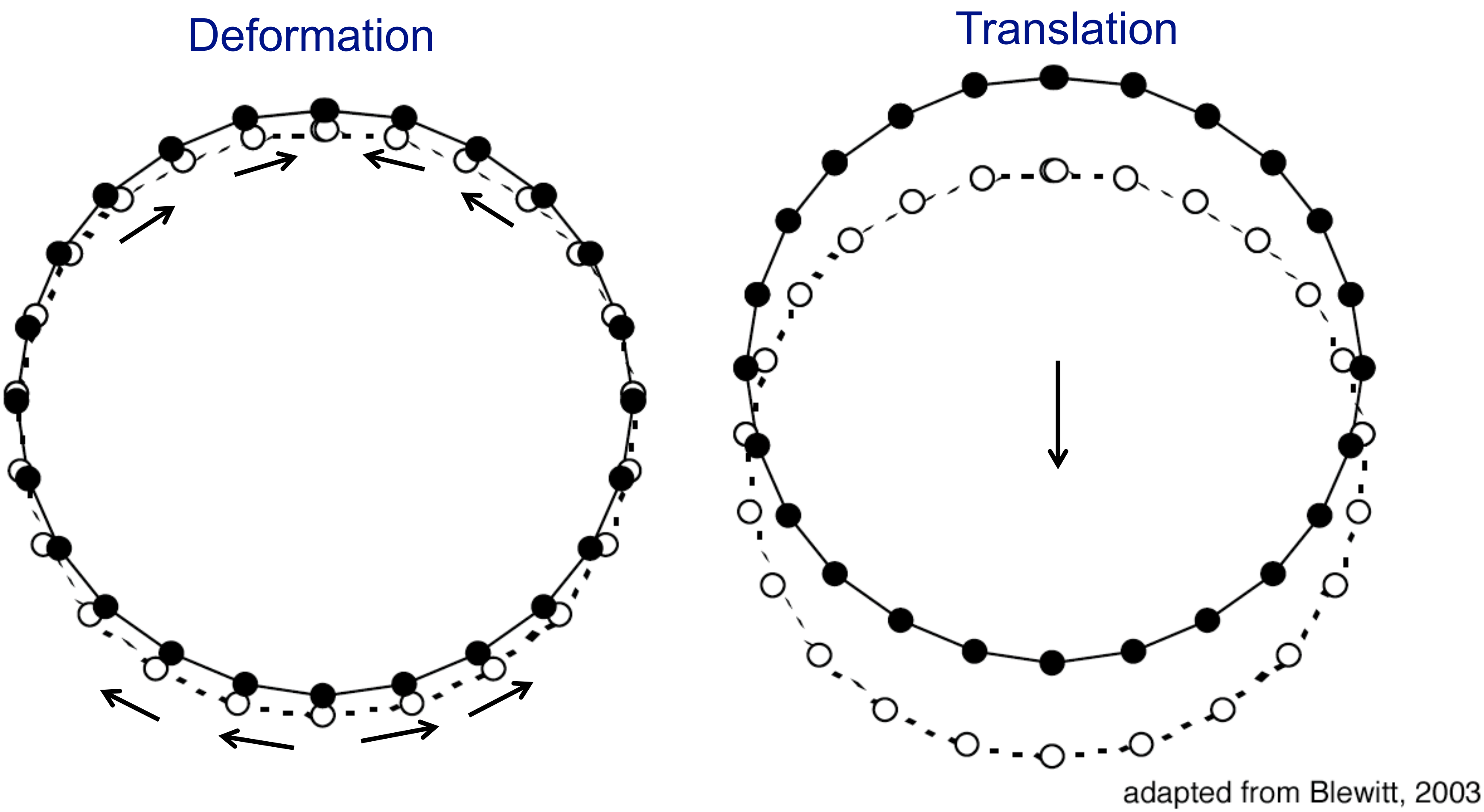
The geographical distribution of the MSL from the CoM omission error



(Melachroinos et al., 2013)

Fig. 5 Observed geographical MSL error (in mm) resulting from the geocenter motion model of the *SLR/DORIS* stations from Cheng et al. (2010) for Jason-2 cycle 058 (Jan 28-Feb 07, 2010)

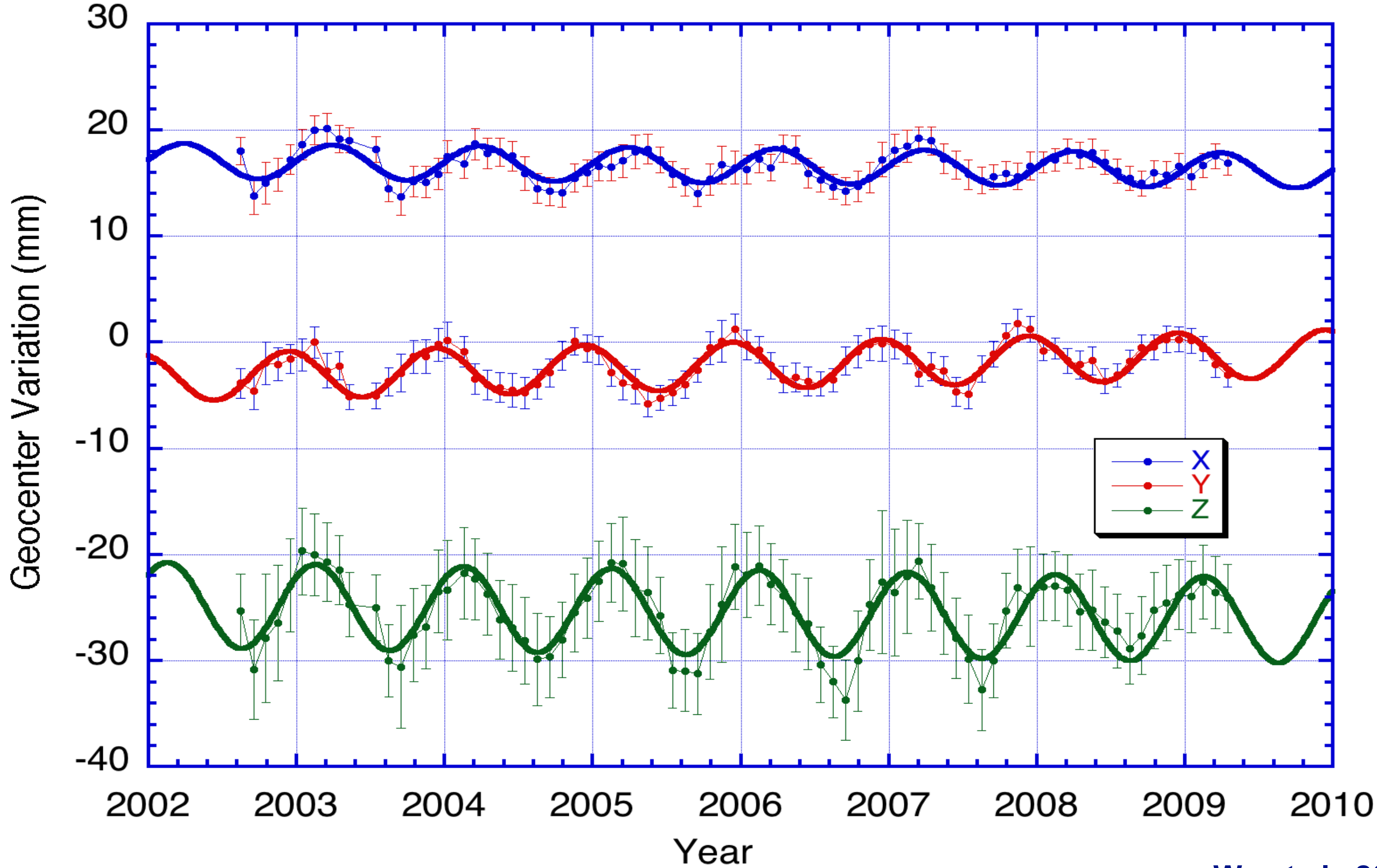
Degree-1 mass redistribution signal



While both are occurring, different techniques tend to concentrate on just one aspect (efforts have been made to capture both, with mixed results)

Global Inversion Approach (1)

Estimate degree-1 deformation from GPS, using other information (GRACE, Ocean bottom pressure, etc.) to remove load signal above degree 1



Wu et al., 2010

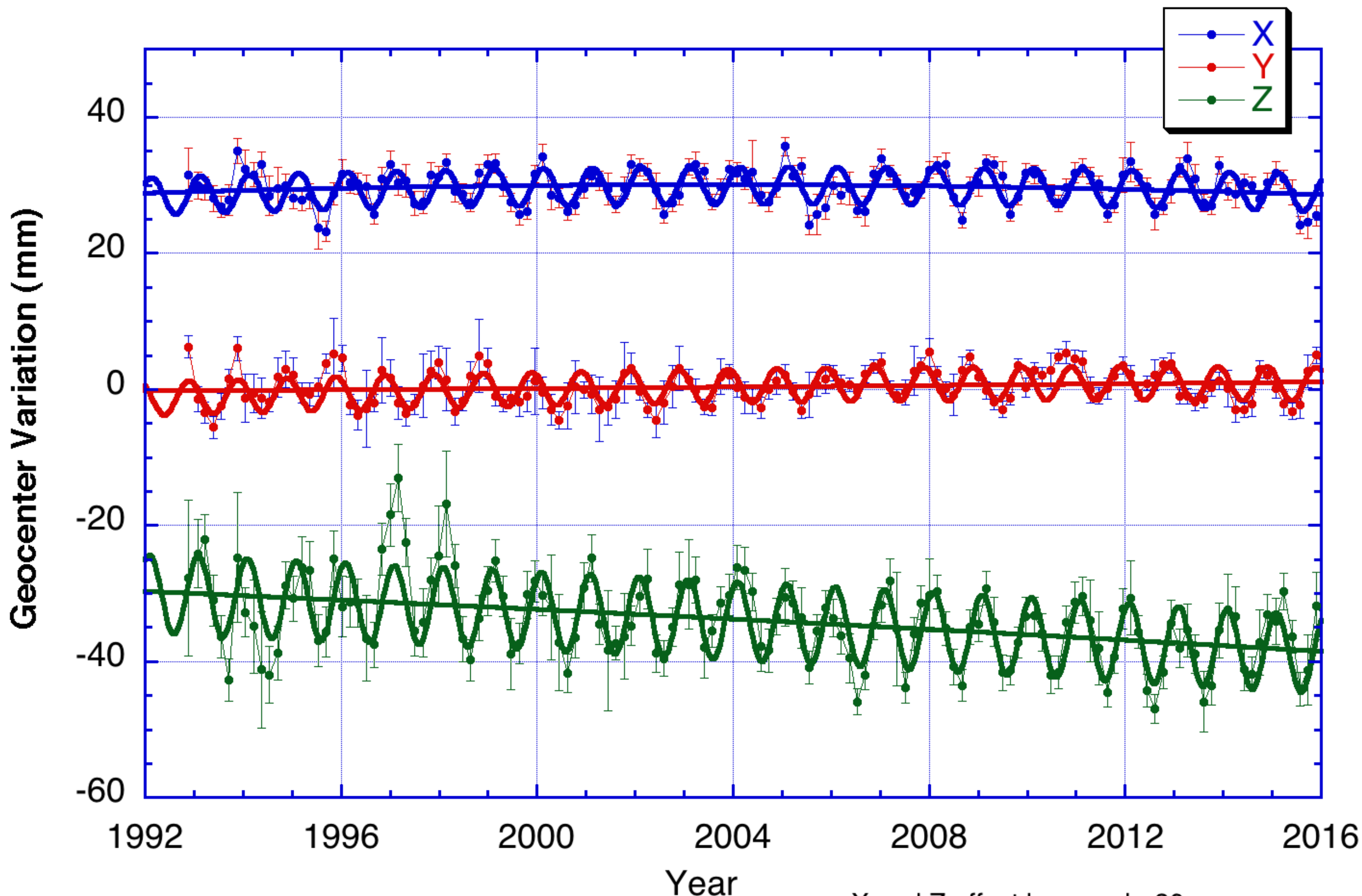
Global Inversion Approach (2)

Estimate degree-1 deformation from GPS, using other information (GRACE, Ocean bottom pressure, etc.) to remove load signal above degree 1

GPS Global Inversion	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments)
GPS loading + GRACE + OBP	1.8	46	2.5	329	3.9	28	Wu et al., 2006
GPS loading + GRACE	2.0	21	2.6	334	3.6	24	Jansen et al., 2009
GPS loading + GRACE + OBP	2.0	62	3.5	322	3.1	19	Rietbroeck et al., 2011 (updated June 2011)
GPS loading + GRACE + OBP	1.8	49	2.7	329	4.2	31	Wu et al., 2010
GPS loading + GRACE + OBP	1.9	25	3.3	330	3.7	21	Wu & Heflin, 2014
mean	1.9	41	2.9	329	3.7	25	
standard deviation	0.1	17	0.4	4	0.4	5	

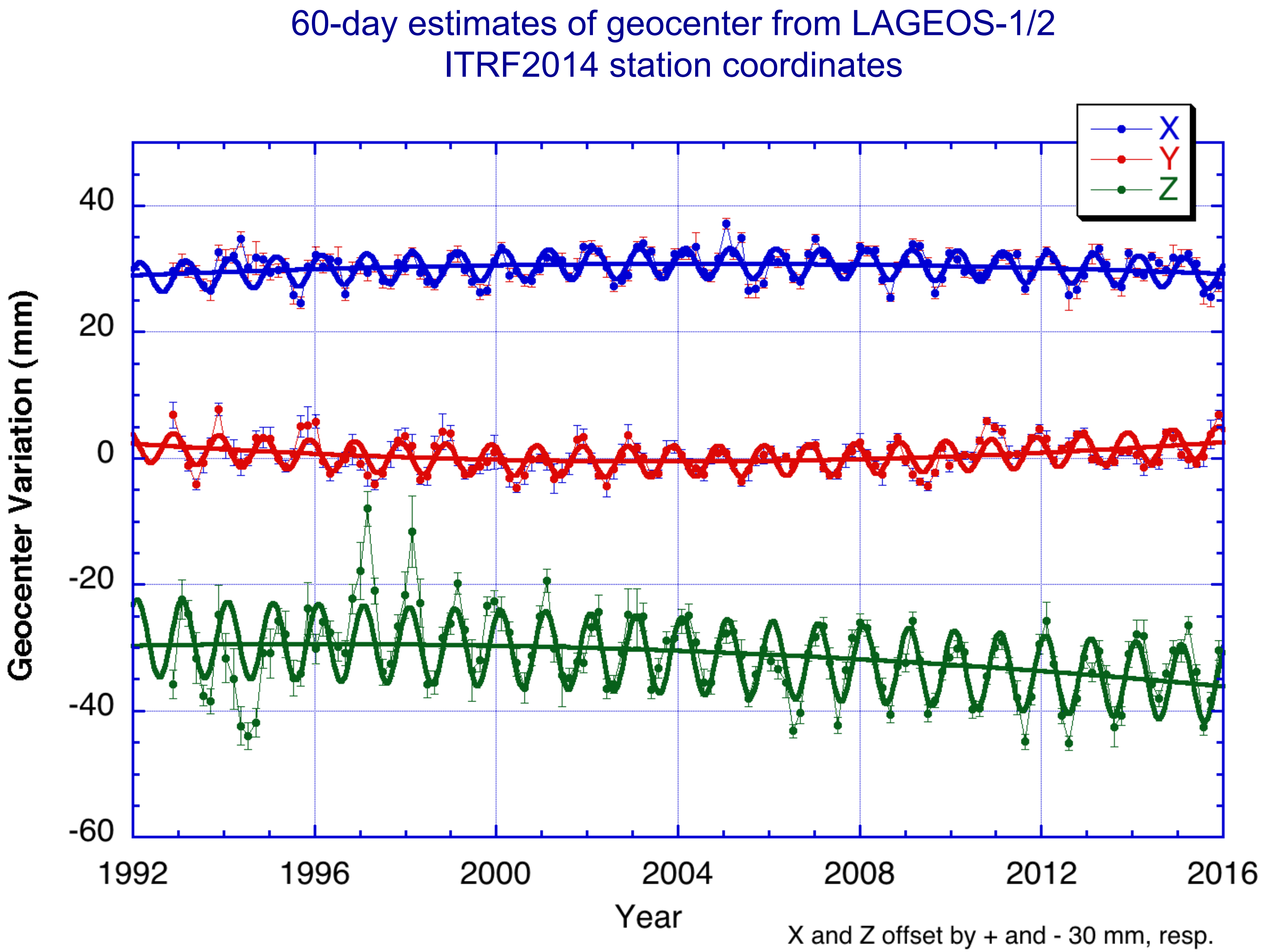
Geocenter Motion from SLR (1)

60-day estimates of geocenter from LAGEOS-1/2
SLRF2005/LPOD2005 station coordinates



X and Z offset by + and - 30 mm, resp.

Geocenter Motion from SLR (2)



Geocenter Motion from SLR (3)

SLR results	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments)
SLR (ILRS)	2.6	40	3.1	315	5.5	22	Altamimi et al., 2011 (ILRS contribution to ITRF2008)
SLR (5 satellites)	2.7	40	2.8	323	5.2	30	Cheng et al., 2013 (weekly estimates;1993-2010)
SLR (ILRS)	2.6	46	2.9	320	5.7	28	Altamimi et al., 2016 (ILRS contribution to ITRF2014)
SLR (L1/L2)	2.8	47	2.5	322	5.8	31	Ries, 2016 (60-day estimates; 1993-2016)
SLR (L1/L2)	2.4	55	2.5	321	6.1	31	Ries, 2016 (60-day estimates; 1993-2016) ITRF2014
mean	2.6	46	2.8	320	5.7	28	
standard deviation	0.1	6	0.3	3	0.3	4	(CN-CM)
Previous results	2.7	41	2.8	321	5.5	27	Ries, 2013 ("Climatological model", AGU presentation)

GPS Global Inversion	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments)
GPS loading + GRACE + OBP	1.8	46	2.5	329	3.9	28	Wu et al., 2006
GPS loading + GRACE	2.0	21	2.6	334	3.6	24	Jansen et al., 2009
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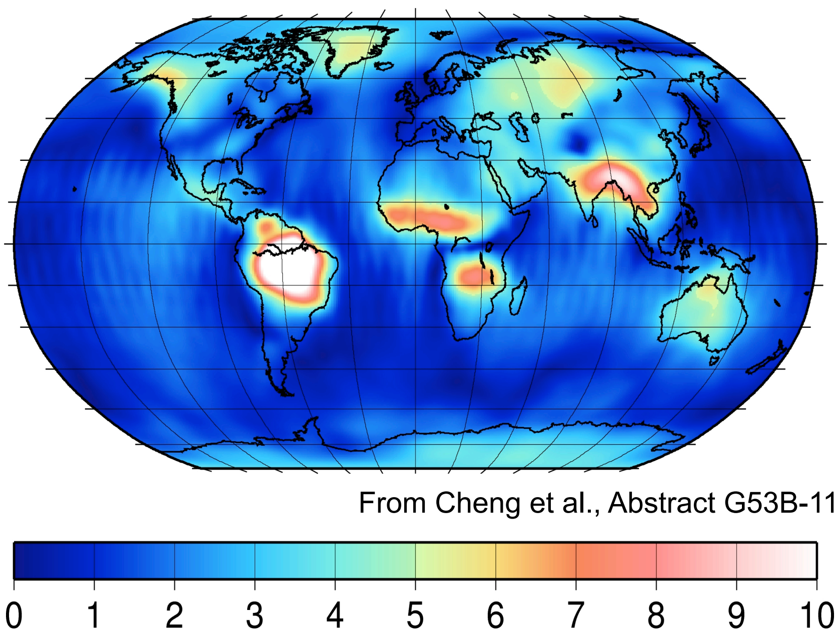
GPS loading + GRACE + OBP	1.9	25	3.3	330	3.7	21	Wu & Heflin, 2014
mean	1.9	41	2.9	329	3.7	25	(CF-CM)
standard deviation	0.1	17	0.4	4	0.4	5	

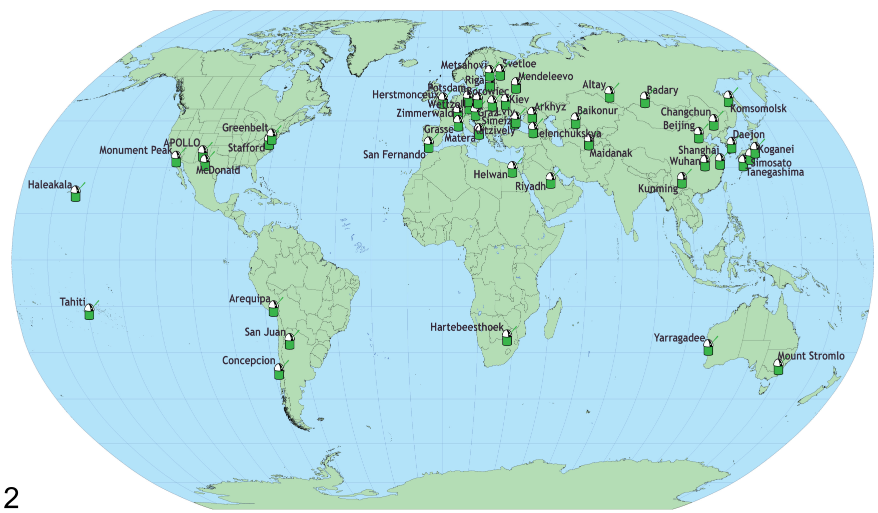
‘Network Effect’

- Geocenter translation estimates from SLR will be affected by local loading (in fact, this applies to all techniques, not just SLR)
- Effect is minimized for SLR due to stations being located in generally benign mid-latitudes, but likely still significantly biasing SLR estimates



From Cheng et al., Abstract G53B-1137, 2012

Annual vertical deformation from GRACE (mm)
(horizontal is sub-mm at mid-latitudes)



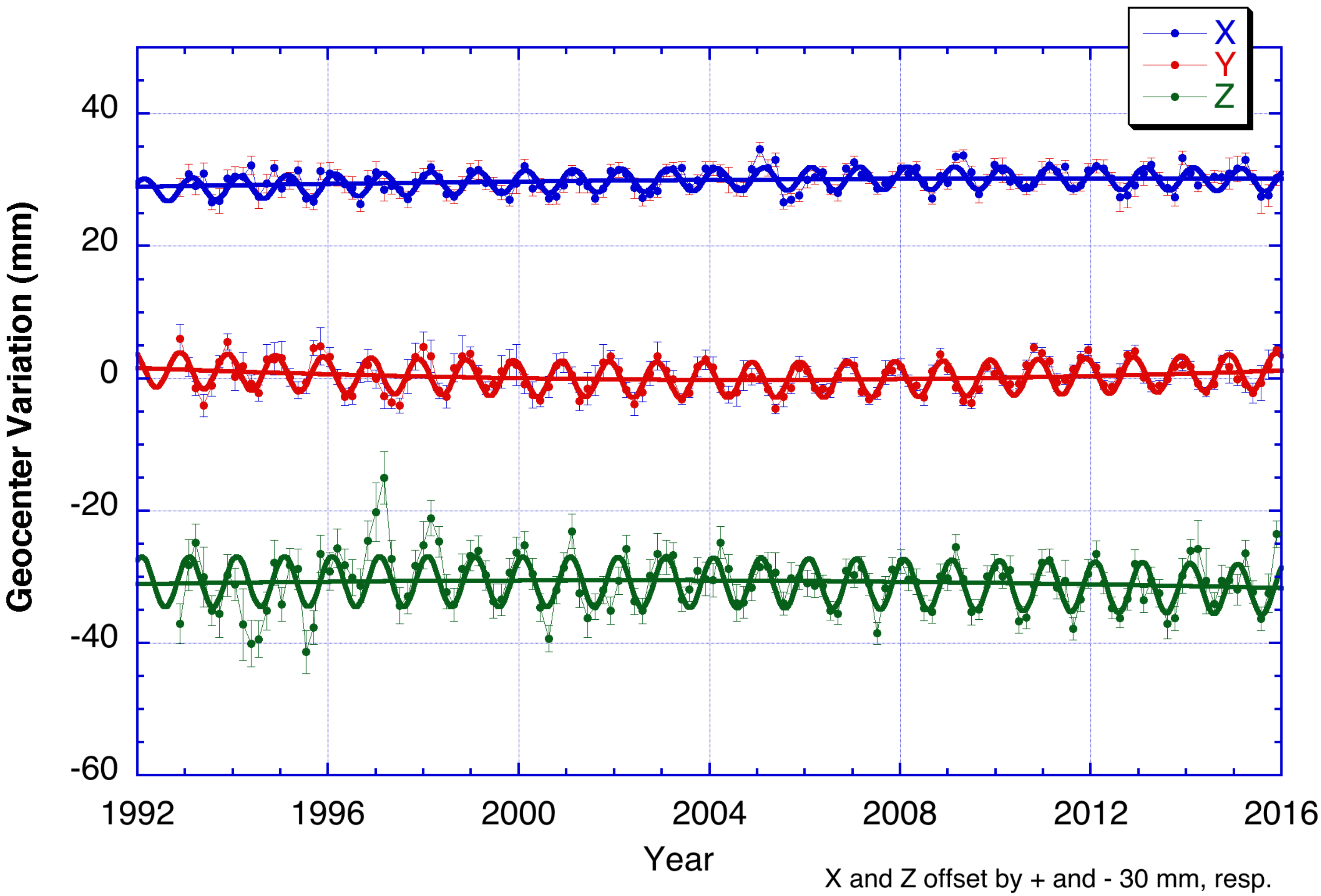
ILRS network

Addressing 'Network Effect'

- Simply forward-modeling the non-tidal atmosphere loading (NTAL) will also remove part of the degree-1 signal of interest
  - One approach would be to apply NTAL without the degree-1 part
  - Would need to do the same thing for the hydrological loading
- Alternatively, use GPS global inversion approach of using GRACE for degree-2 and above, but this is possible only during the GRACE mission
- Given the limitations of these approaches, try to see if the data itself can provide a solution
  - Since local site loading would be dominated by vertical motion (especially at SLR sites), estimate the bias for every site on the same cadence (monthly or 60-day) to absorb local vertical signals (and any actual biases)
  - Applying a relatively tight *apriori* to the bias (~2.5-3.0 sigma) allows the common mode signal from geocenter to go to the geocenter parameters (no constraint) while the local motion that is not common mode has a place to go

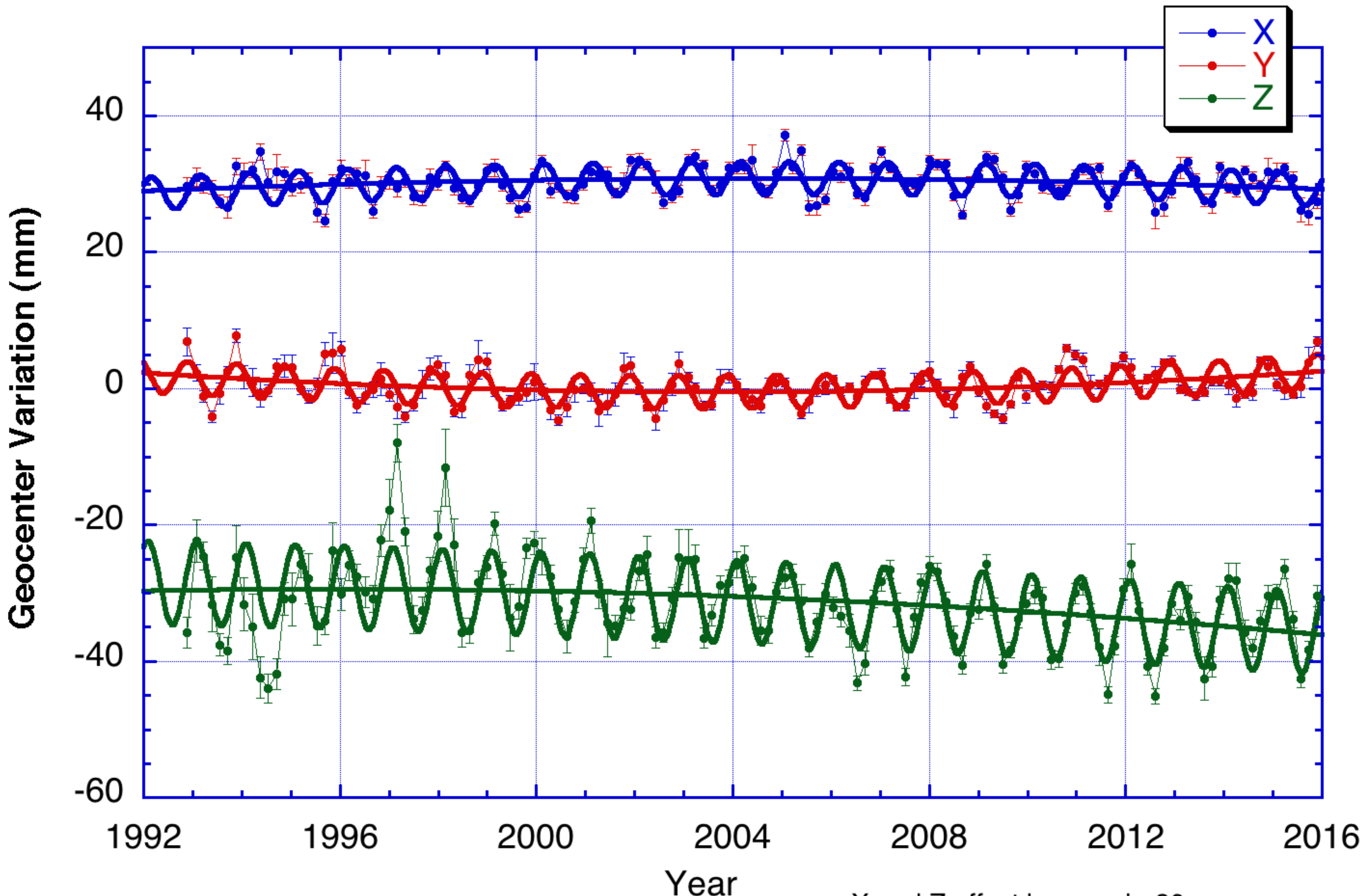
Updated Geocenter Motion from SLR

60-day estimates of geocenter from LAGEOS-1/2
ITRF2014 station coordinates, estimate biases 5 mm constraint



Geocenter Motion from SLR (2)

60-day estimates of geocenter from LAGEOS-1/2
ITRF2014 station coordinates



X and Z offset by + and - 30 mm, resp.

SLR Estimates now agree well with GPS Global Inversion

SLR results	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments)
SLR (L1/L2)	2.0	47	2.8	322	3.9	27	Ries, 2016 (60-day 1993-2016, 5 mm biases)
SLR (L1/L2)	1.8	52	2.7	321	3.8	30	Ries, 2016 (60-day 1993-2016, 5 mm biases ITRF2014)
SLR (L1/L2)	2.0	48	2.9	321	4.0	26	Ries, 2016 (30-day 1993-2016, 7.5 mm biases)
SLR (L1/L2)	1.8	52	2.8	321	3.9	30	Ries, 2016 (30-day 1993-2016, 7.5 mm biases ITRF2014)
mean	1.9	50	2.8	321	3.9	28	
standard deviation	0.1	3	0.1	1	0.1	2	(CF-CM)
GPS Global Inversion	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments)
GPS loading + GRACE + OBP	1.8	46	2.5	329	3.9	28	Wu et al., 2006
GPS loading + GRACE	2.0	21	2.6	334	3.6	24	Jansen et al., 2009
GPS loading + GRACE + OBP	2.0	62	3.5	322	3.1	19	Rietbroeck et al., 2011 (updated June 2011)
GPS loading + GRACE + OBP	1.8	49	2.7	329	4.2	31	Wu et al., 2010
GPS loading + GRACE + OBP	1.9	25	3.3	330	3.7	21	Wu & Heflin, 2014
mean	1.9	41	2.9	329	3.7	25	
standard deviation	0.1	17	0.4	4	0.4	5	

New Climatological model	1.9	45	2.9	325	3.8	26	Average of SLR and GPS global inversion
standard deviaton	0.1	10	0.3	2	0.2	3	

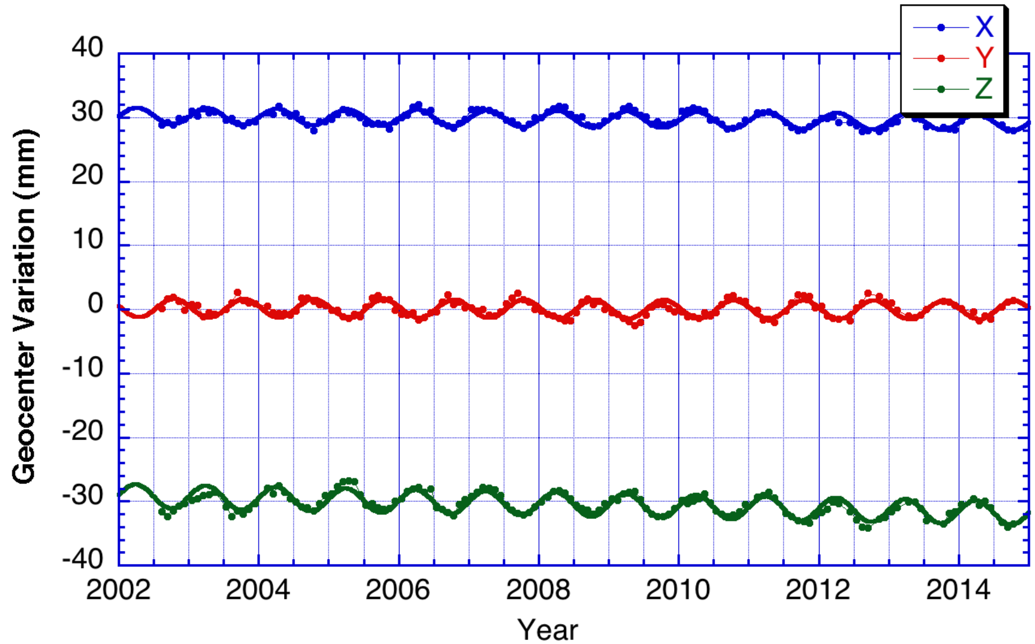
Compare to Ensemble of 'Reasonable' Estimates* (Ries, 2013)

Geodetic observations	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments) (phase is in degrees)
SLR (L1/L2)	2.2	59	3.2	299	2.8	45	Eanes et al., 1997; Chen et al., 1999
SLR/DORIS/GPS	2.9	58	3.7	304	4.5	3	Montag, 1999
SLR	2.1	47	2.0	322	3.5	42	Bouille et al., 2000 (errors estimated to be 0.5-1.5 mm for amplitudes)
Topex/Poseidon (SLR/DORIS)	1.8	41	2.9	320	2.4	37	Eanes & Ries, 2000
SLR (L1/L2)	2.6	32	2.5	305	3.3	35	Creteaux et al., 2002
SLR (L1/L2)	1.3	45	2.2	321	2.6	31	Eanes, 2005 (12-year series of weekly solutions; scale also adjusted)
GPS	2.1	42	3.2	343	3.9	77	Lavallée et al., 2006 (errors estimated to by 0.5-0.8 mm and ~20° phase)
GPS loading + GRACE + OBP	1.9	42	3.2	328	3.6	25	Wu, 2006
SLR (ILRS)	2.7	45	3.8	327	3.6	4	Collilieux et al., 2009 (translation model; no scale)
SLR (ILRS)+GPS+OBP	2.4	32	2.6	322	5.3	23	Collilieux et al., 2009 (translation model estimated with inverse loading model)
SLR (ILRS)+loading model	3.7	34	1.8	324	3.7	34	Collilieux et al., 2009 (translation model estimated with forward loading model)
GPS + OBP	1.3	6	3.0	338	4.6	23	Coullilieux et al., 2009 (Inverse model, GPS+OBP)
SLR(ILRS)+GPS	2.5	19	3.2	327	3.4	17	Collilieux et al., 2009 (use GPS to correct for loadingl)
GPS loading + GRACE	2.0	21	2.6	334	3.6	24	Jansen et al., 2009
GPS loading + GRACE + OBP	1.8	49	2.7	325	4.2	31	Wu et al., 2010
SLR (ILRS)	2.6	40	3.1	315	5.5	22	Altamimi et al., 2010 (ILRS contribution to ITRF2008)
SLR (5 satellites)	2.7	40	2.8	323	5.2	30	Cheng et al., 2010 (weekly estimates of 5x5 gravity and geocenter, 1993-2010)
SLR (5 satellites)	2.9	35	2.6	306	4.2	44	Cheng et al., 2010 (monthly estimates of 5x5 gravity and geocenter, 2002-2010)
GPS loading + GRACE + OBP	2.0	62	3.5	322	3.1	19	Rietbroeck et al., 2011 (updated June 2011)
GRACE+Ocean Model	2.2	43	3.0	333	2.7	42	Swenson, Chambers & Wahr, 2008 (GRACE + OMCT) (updated 2012)
SLR (L1/L2)	2.9	43	2.6	323	6.0	37	Ries, 2013 (30-day estimates; 1993-2012; estimate 2x2 gravity)
SLR (L1/L2)	2.8	47	2.6	324	5.8	34	Ries, 2013 (60-day estimates; 1993-2012)
Mean (mm)	2.3	40	2.9	322	4.0	31	
Stdev (mm)	0.6	13	0.5	11	1.1	15	

* "reasonable" arbitrarily defined as realistic estimates in all 3 coordinates

Updated CF-CM Model Improves Consistency with GRACE + OBP Global Inversion

The only regularly delivered product for degree-1 variations consistent with the GRACE "GSM" products is from Swenson, Chambers & Wahr, 2008



Comparison	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	
New 'Climatological' model	1.9	45	2.9	325	3.8	26	Full degree-1 (AOD not removed)
GRACE+Ocean Model	2.2	43	3.0	333	2.7	42	SCW, 2008 (updated 2012, AOD restored)
Geophysical models	2.3	31	2.2	333	3.1	33	Mean of 8 geophysical models
AOD	1.3	9	1.6	350	0.9	364	AOD1b (RL05, 2002-2014) (GAC)
Climatological model wo AOD	1.3	86	1.5	293	3.3	34	Degree-1 with AOD removed (GSM)
GRACE+Ocean Model	1.3	92	1.4	282	1.8	87	SCW, 2008 (updated 2012, AOD not restored)

Summary

- The nominal SLR estimates of geocenter motion are consistent with the IERS conventions of a correction to center the ITRF on the mass center of the Earth
  - Applying this correction improves the centering of SLR-based orbits
  - This "CN-CM" correction is likely applicable to DORIS as well, as the same sort of local site motion will affect SLR/DORIS orbits
  - This correction is not appropriate if NATL is being forward-modeled, but rather, the "CF-CM" model should be more appropriate (ideally, the degree-1 component should not be included in the NATL)
- By providing an accomodation for the local (spurious) site motion, the estimates of annual geocenter motion from SLR finally become aligned with those from GPS/GRACE/OBP global inversion
- After removing the contribution from the atmosphere/ocean (AOD1B), the SLR/GPS results agree well with Swenson et al., except for the Z component (GRACE/OBP inversion appears to miss some of the signal)