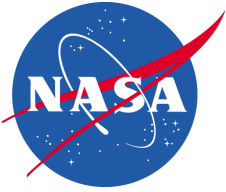


Time-variable Gravity Effects on LEO Satellites

F.G. Lemoine

*Unified Analysis Workshop
Pasadena, California
June 27-28, 2014*



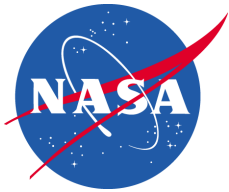
Geopotential Modelling (Motivation)



- GRACE (+ GOCE) have provided detailed models of the Earth's static gravity field and its time-variations, but only since ~2003.
- The models, applied to altimetry satellite orbit analysis show big improvements in orbit accuracy – one of the contributors to doing orbits on Jason-2 with SLR fits ~ 1 cm.

Issues:

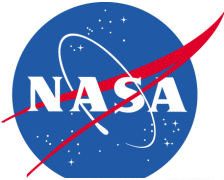
- (1) Models are so detailed that they are effectively 'tuned' to the period of the GRACE mission;
- (2) The early models (EIGEN-GL04S1), GGM02C/S, GGM03S, EGM2008 – show degradation starting in 2008.
- (3) No real strategy for developing a coherent model that is valid over entire time period of altimeter satellite data (~1993-2013) or ITRF data period (1983-2013).



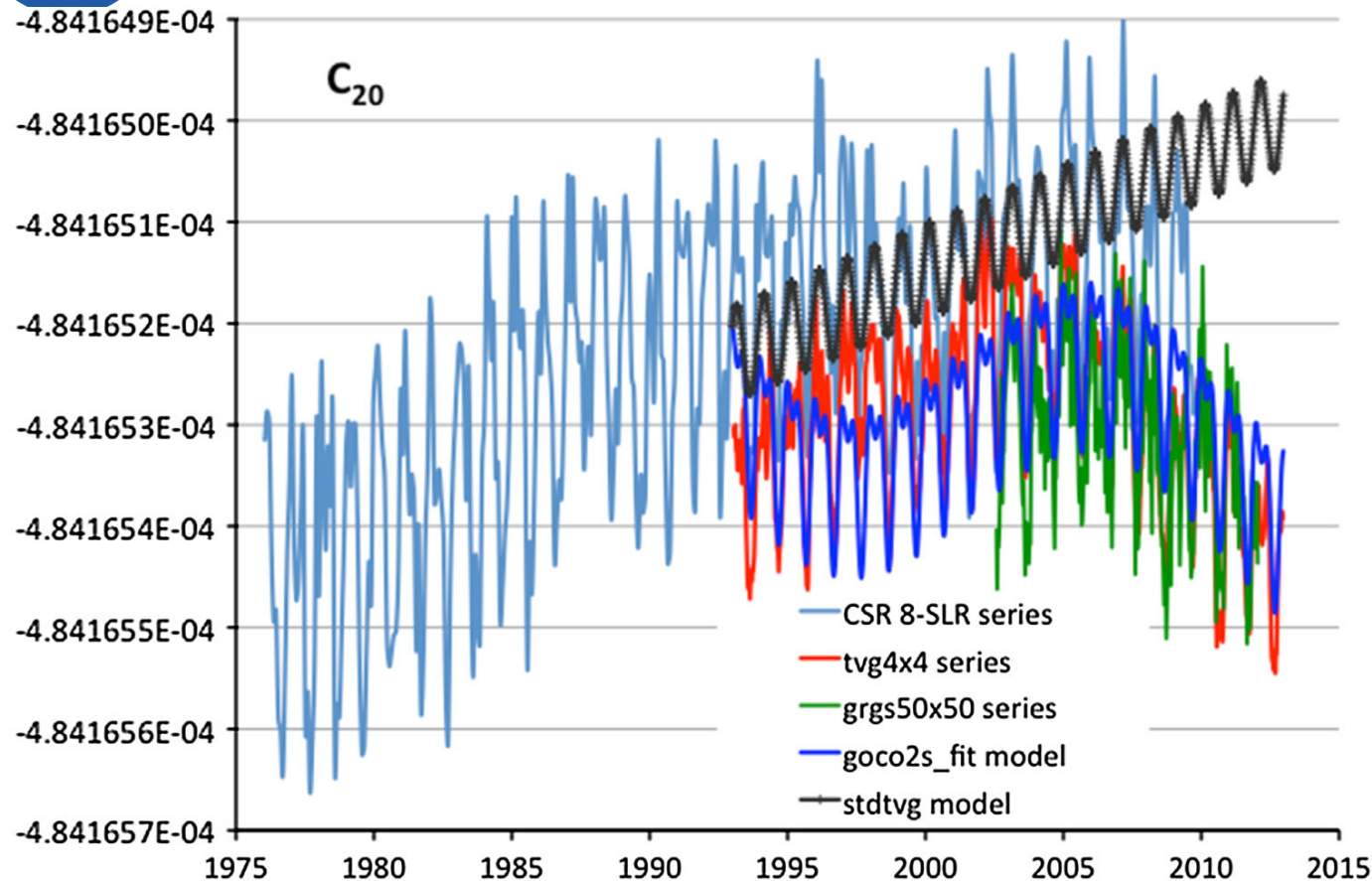
Time-Variable Gravity Modelling



Model Type	Example
Time Series	(A) Monthly Solutions GRACE Analysis Centers: (CSR, GFZ, JPL, ...) (B) ~10-day solutions (GRACE+Lageos) (GRGS). (C) Smoothed weekly solutions (NASA GSFC, SLR+DORIS) 5x5 + GRACE annual harmonics for higher degrees.
Comprehensive	Single Solution over a finite time span. e.g. Eigen6s: (2003 – 2009.5). Static, TVG, 50x50 Rates, Annual, Semiannual
Tailored	Eigen6s2 TVG. bias/annual terms/year, extended backward pre 2002 with values of 2002; C20 solution from Lageos time series.
Static-only	GOCO02S, GOCO3S, GGM05S (no TVG is directly provided)
ITRF2008 (e.g. GGM02C, GGM03, EGM2008)	Rate terms only for C_{20} C_{21} , S_{21} C_{30} C_{40}



Example: C_{20} (1)



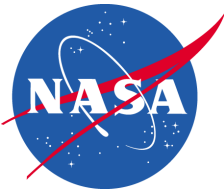
(Zelensky et al., 2014,
J. Geodesy, Figure 1)

CSR 8-SLR: (M K Cheng et al.)

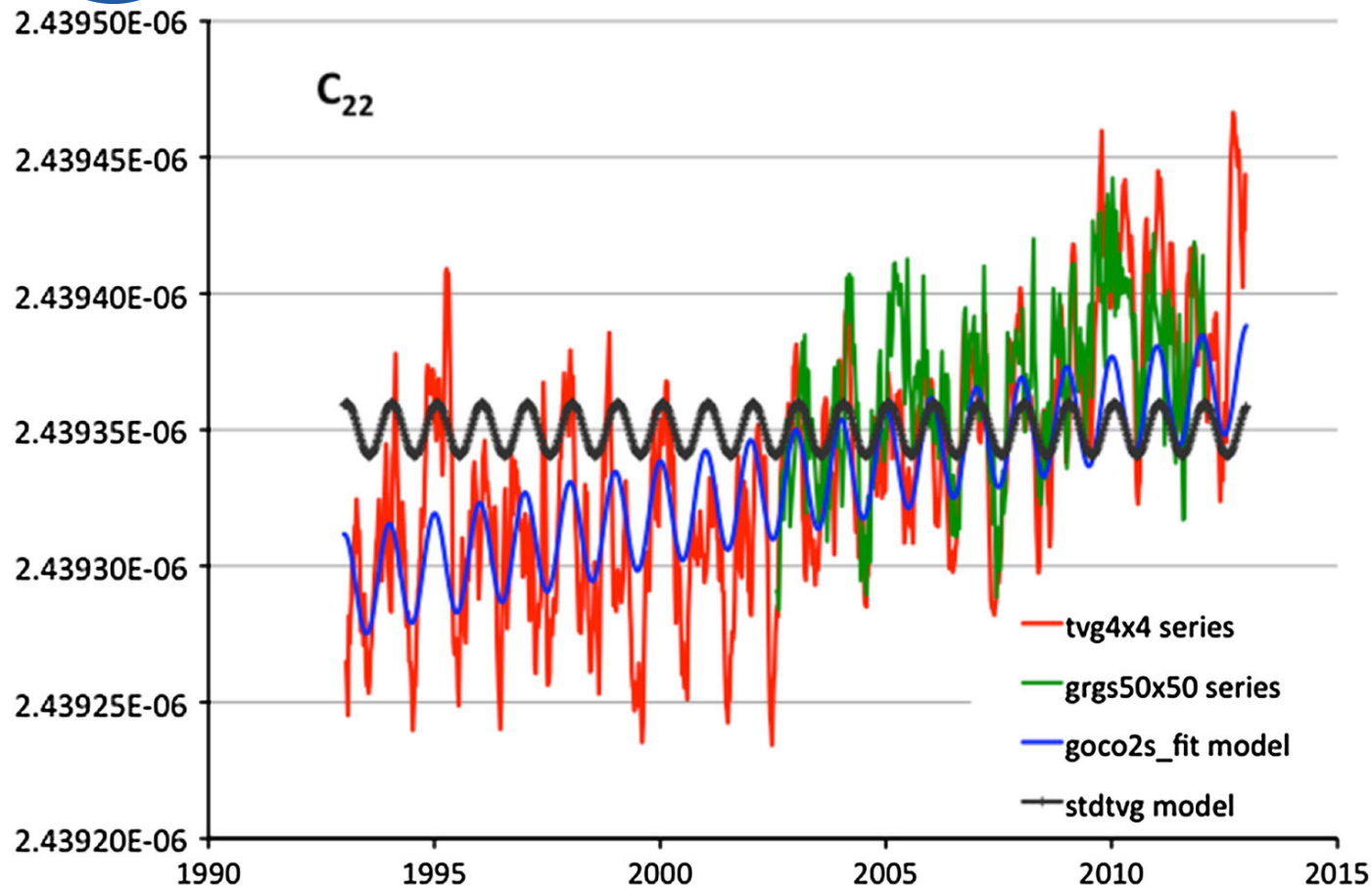
tv4x4: (SLR/DORIS-derived time series, GSFC)

grgs50x50: GRGS time series (GRACE+LAGEOS)

stdtv: C20dot, C30dot, C40dot C21dot, S21dot only +
annuals from GRACE

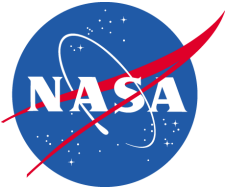


Example: C_{22} (2)

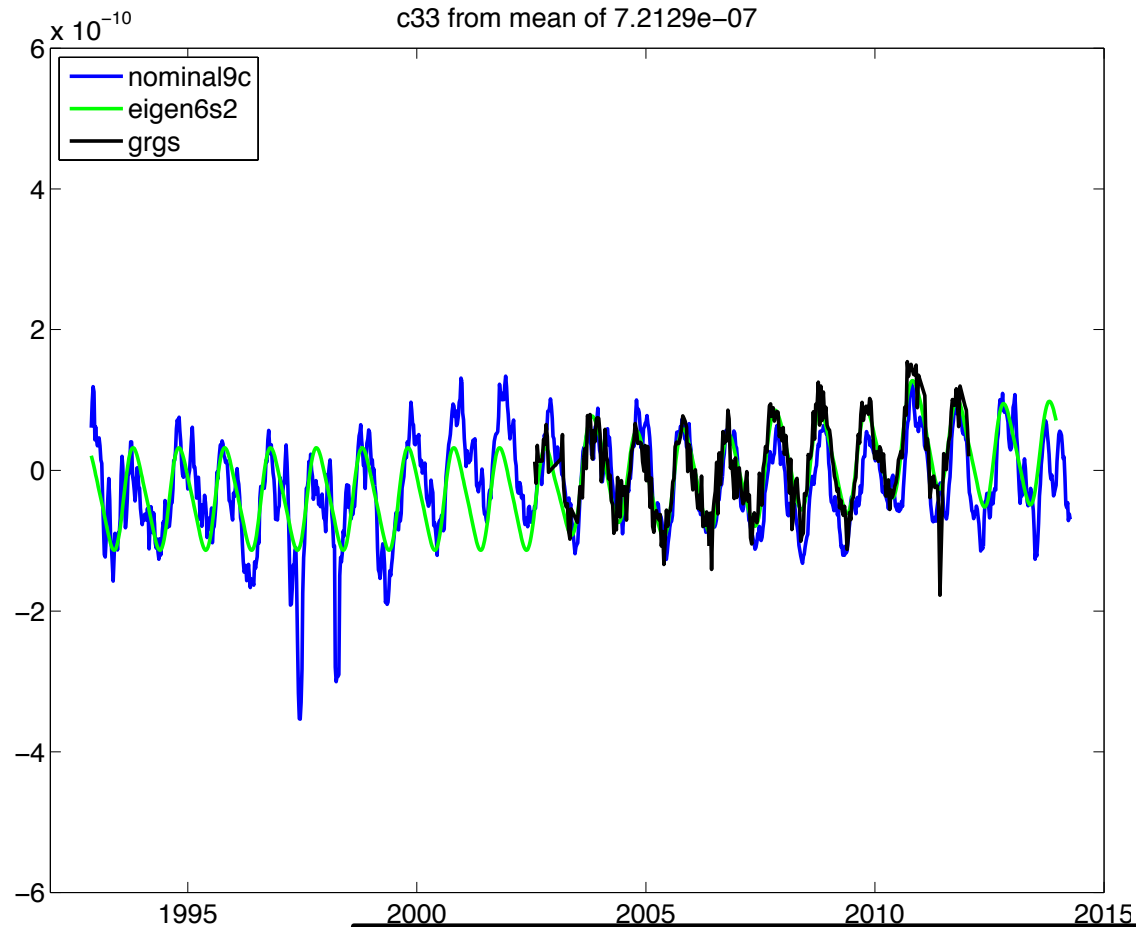


(Zelensky et al., 2014,
J. Geodesy, Figure 2)

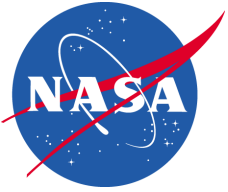
tv4x4: (SLR/DORIS-derived time series, GSFC)
grgs50x50: GRGS time series (GRACE+LAGEOS)
stdtv: C20dot, C30dot, C40dot C21dot, S21dot only +
Annuals (GRACE)



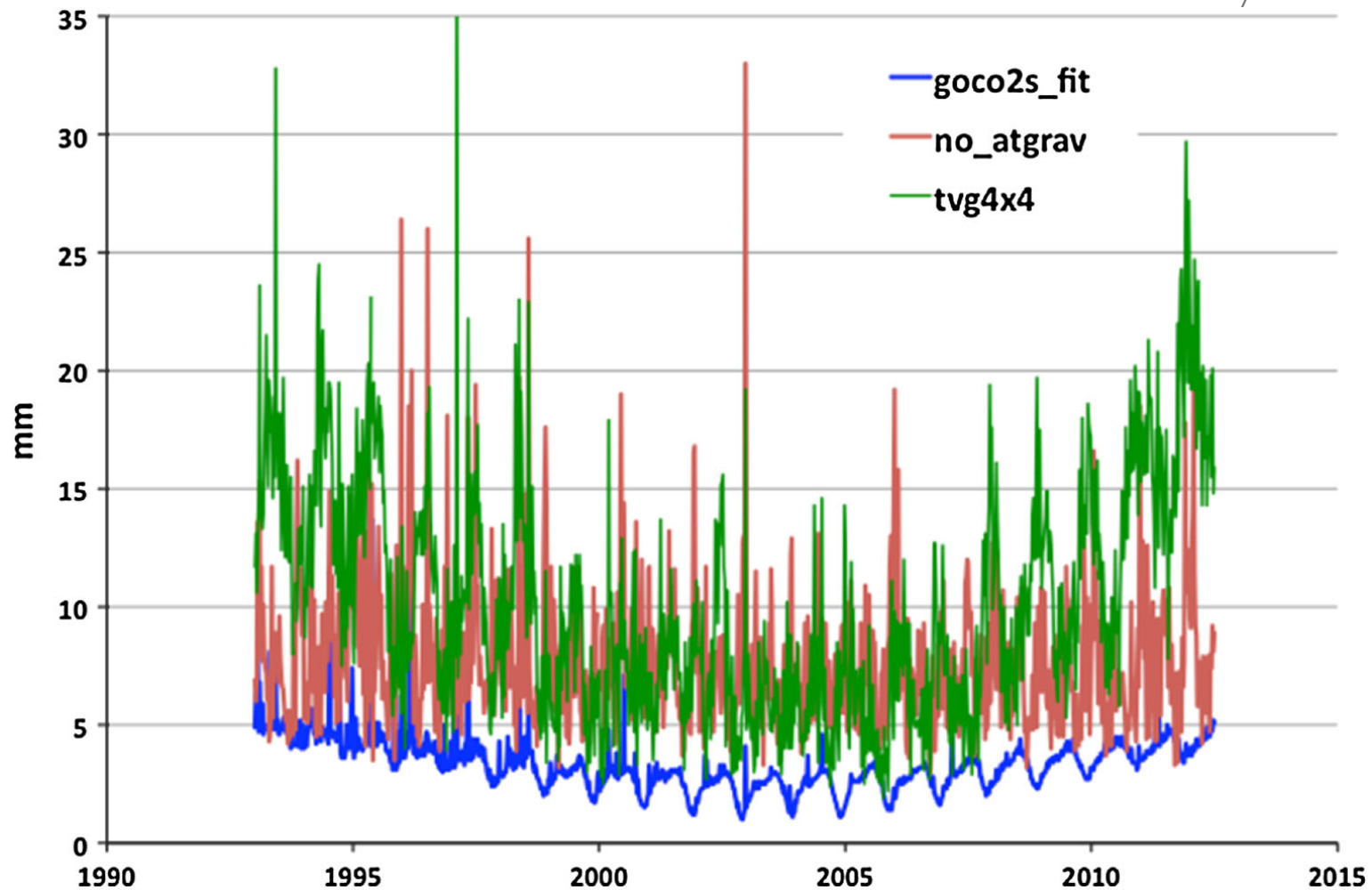
Example: C_{33} (3)



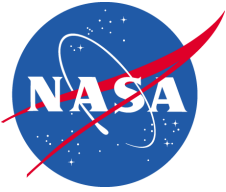
nominal9c: (SLR/DORIS-derived time series, GSFC)
grgs: grgs50x50 time series (GRACE+LAGEOS)
eigen6s2: GRACE+LAGEOS+GOCE, extrapolated pre-GRACE



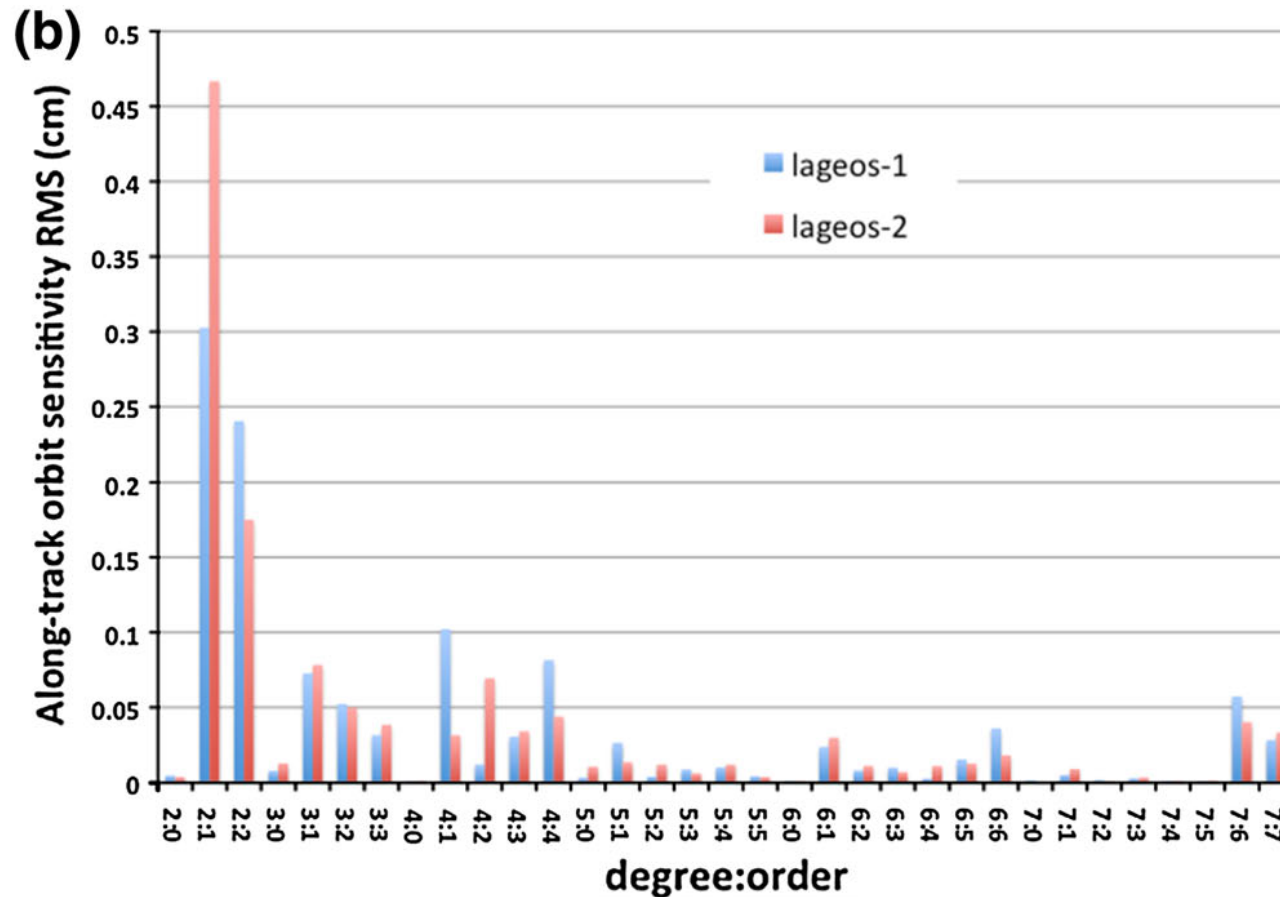
Impact on Lageos1 (1)



(Zelensky et al., 2014, J. Geodesy, Figure 6)

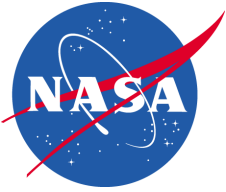


Impact on Lageos1. (2) From Satellite Linear Orbit Perturbations: Time-variable Gravity only (grgs50x50)

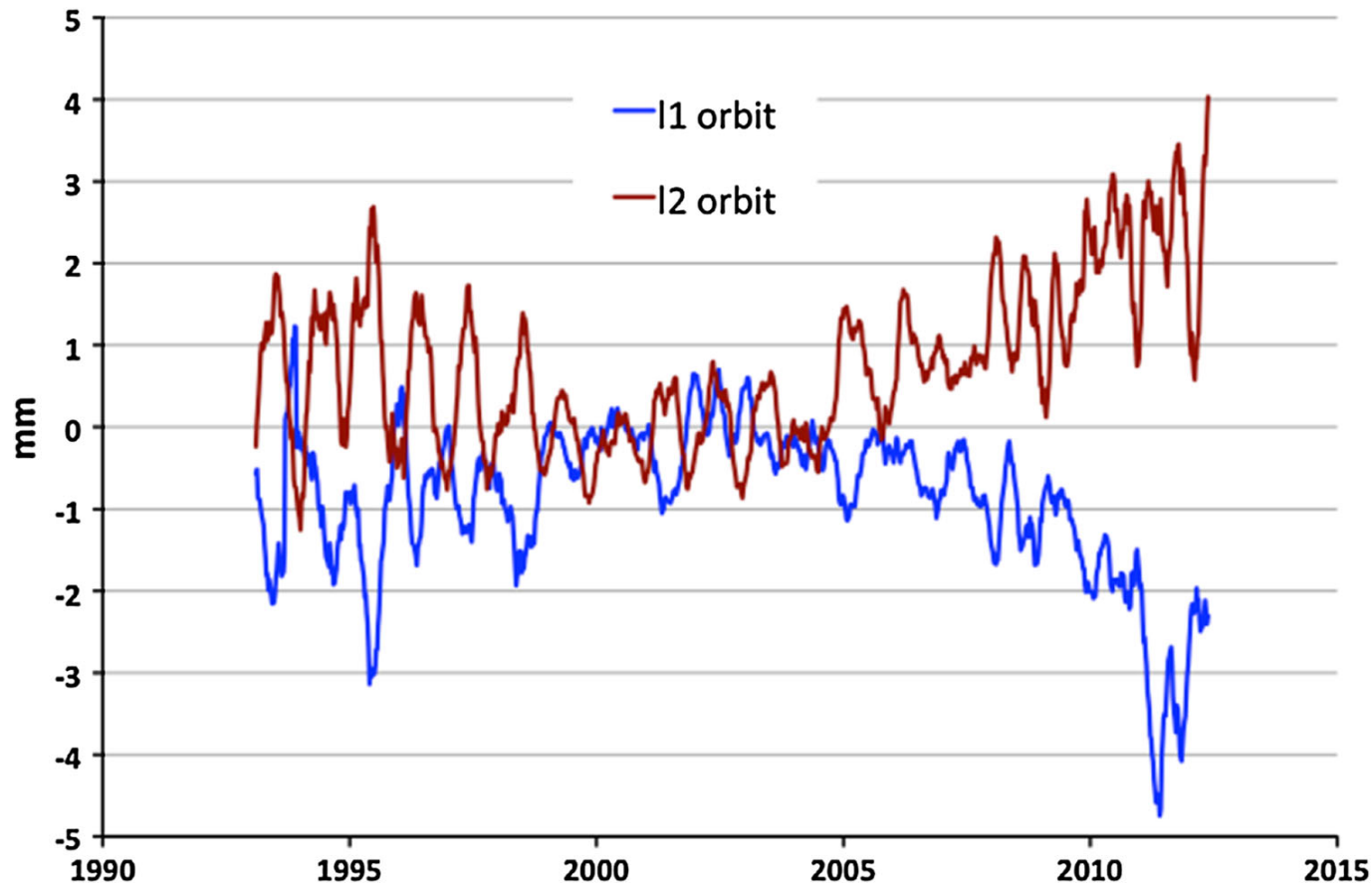


(Exclusive of Secular & Long-Period Perturbations)

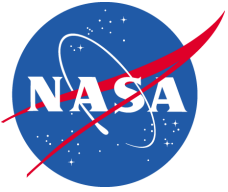
(Zelensky et al., 2014, J. Geodesy, Figure 7)



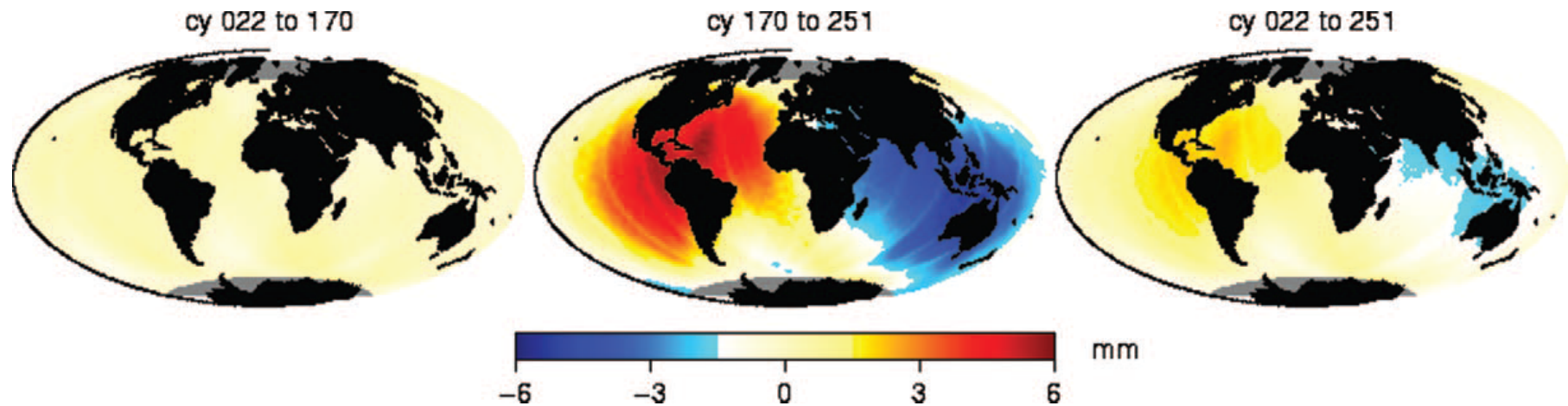
Impact on Lageos1 vs. Lageos2: Tz Helmert transformations between orbits computed with 'EIGEN-GL04S' vs. time series.



(Zelensky et al., 2014, J. Geodesy, Figure 8)

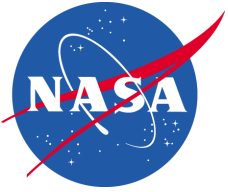


Impact on Jason1 (1): Orbit Impact, Mean

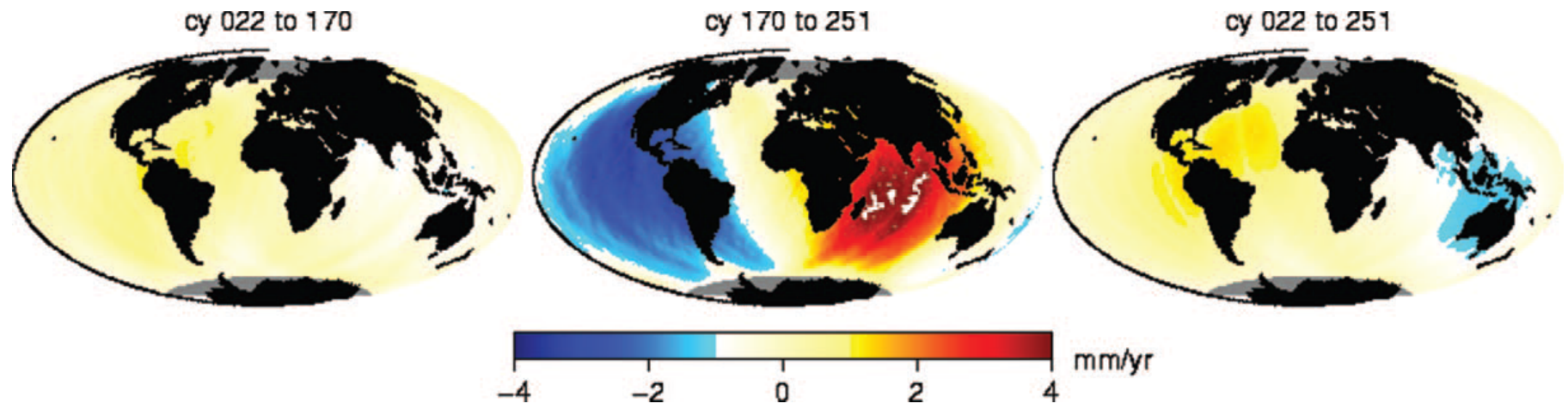


**Mean Radial Orbit difference (mm): EIGEN-GL04s
vs. GRACE GRGS Gravity time series.**
Left: ~2002-2007; Center: ~2007-2009

(Cerri et al., 2010, Marine Geodesy, Figure 13)



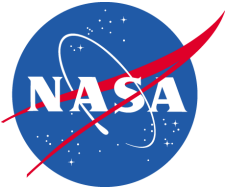
Impact on Jason1 (2): Orbit Impact, Drift



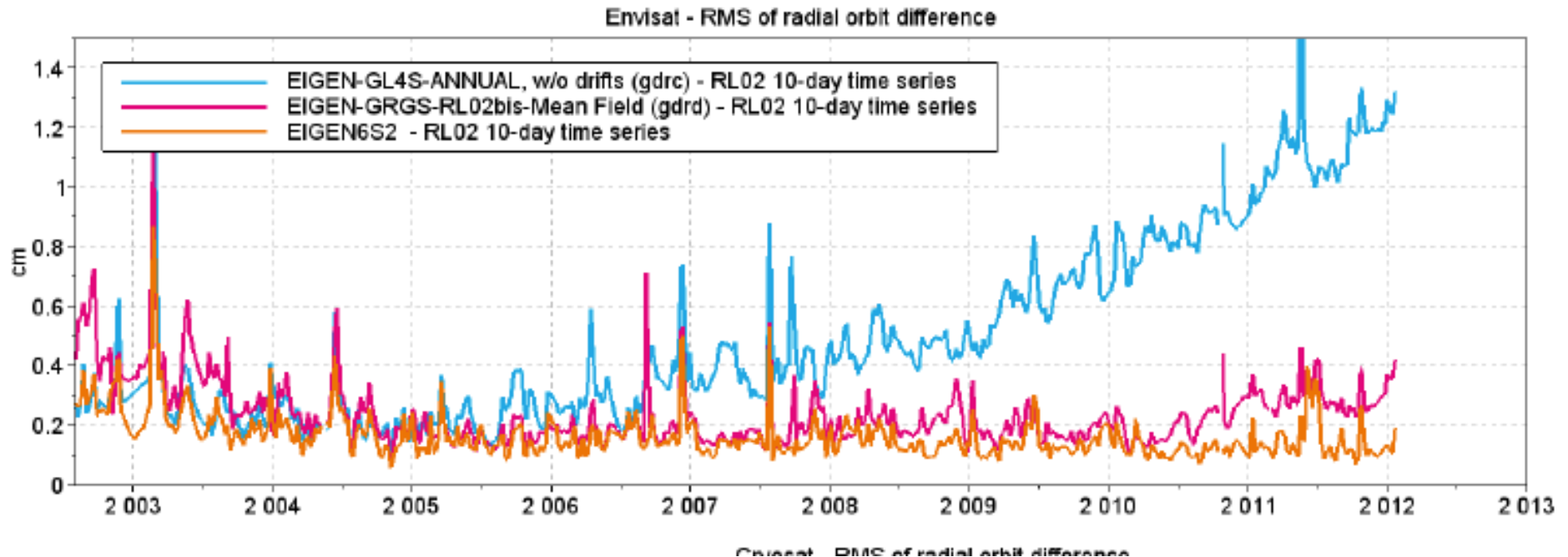
Mean Radial Orbit difference RATE (mm/yr): EIGEN-GL04s vs. GRACE GRGS Gravity time series.

Left: ~2002-2007; Center: ~2007-2009

(Cerri et al., 2010, Marine Geodesy, Figure 14)

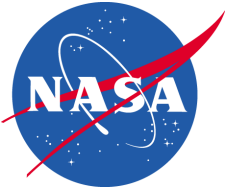


Impact on Envisat: Orbit Impact, Radial RMS

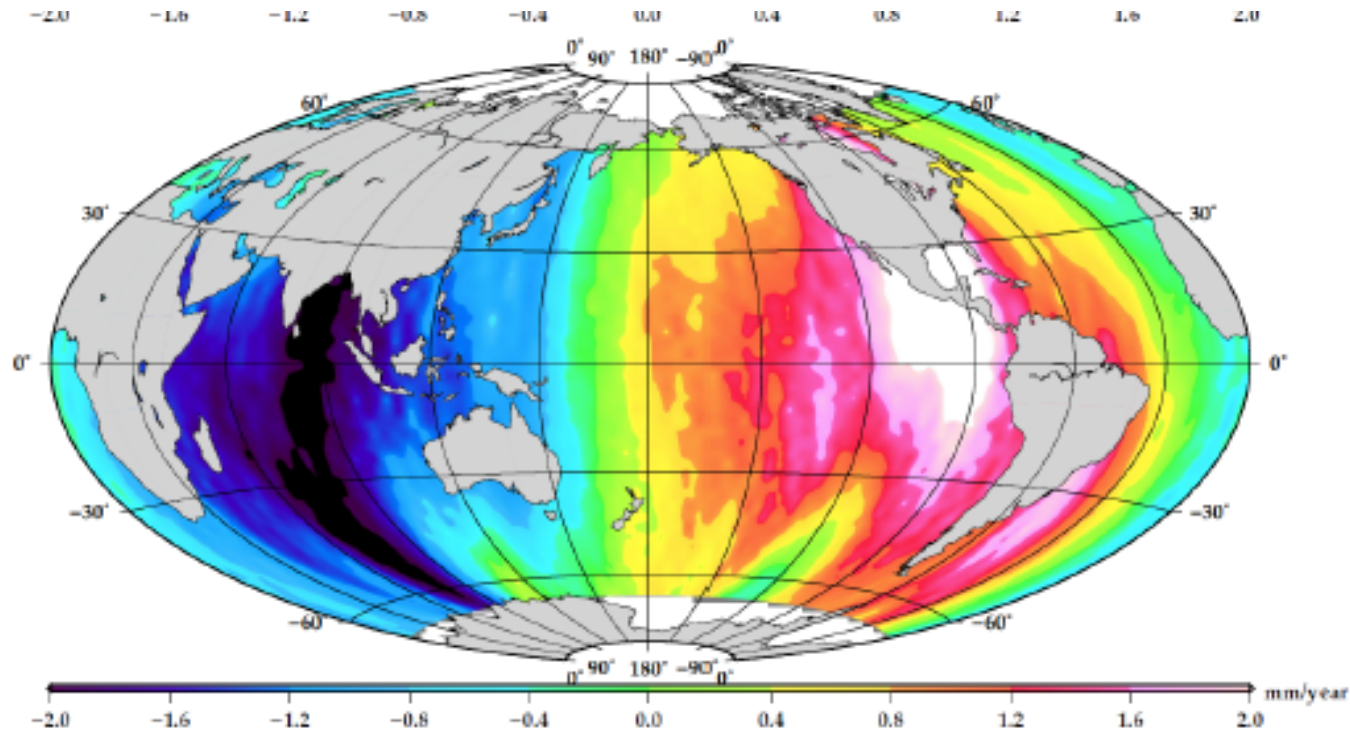


**Envisat; RMS of Radial Orbit Differences (cm) between
TVG representations**

(Cerri et al., October 2013, OSTST meeting, Boulder, Colorado)



Impact on Envisat: Orbit Impact, Rate



**Envisat: RMS of Radial Orbit Difference (2009-2012) Rate (mm/yr)
between GRACE GRGS time series & Eigen6s type field (GDRD)**

(Cerri et al., October 2013, OSTST meeting, Boulder, Colorado)



Impact on Jason2: SLR & Altimeter Crossover RMS of fit (July 2008 – May 2013)



Version	Time-Variable Gravity	SLR Average RMS (cm)	Xover Average RMS (cm)
std1007	EIGEN-GL04S (rate terms in C20, C21, S21, C30 C40 only)	1.194	5.448
std1204	Harmonic fit SLR+DORIS solutions 1993-2012	1.071	5.376
+iers2010	(same as std1204)	1.074	5.378
tv5x5	SLR+DORIS-derived time series (1993-2012)	1.053	5.364
GDRD	Eigen6s-type “Comprehensive solution” (2011)	1.312	5.378
jpl13a	(GPS-reduced-dynamic)	1.175	5.307

(Lemoine, F & Zelensky N et al. , October 2013, OSTST meeting, Boulder, Colorado)



Impact on TOPEX: SLR & Altimeter Crossover RMS of fit (Jan 1993 – Oct 2004)

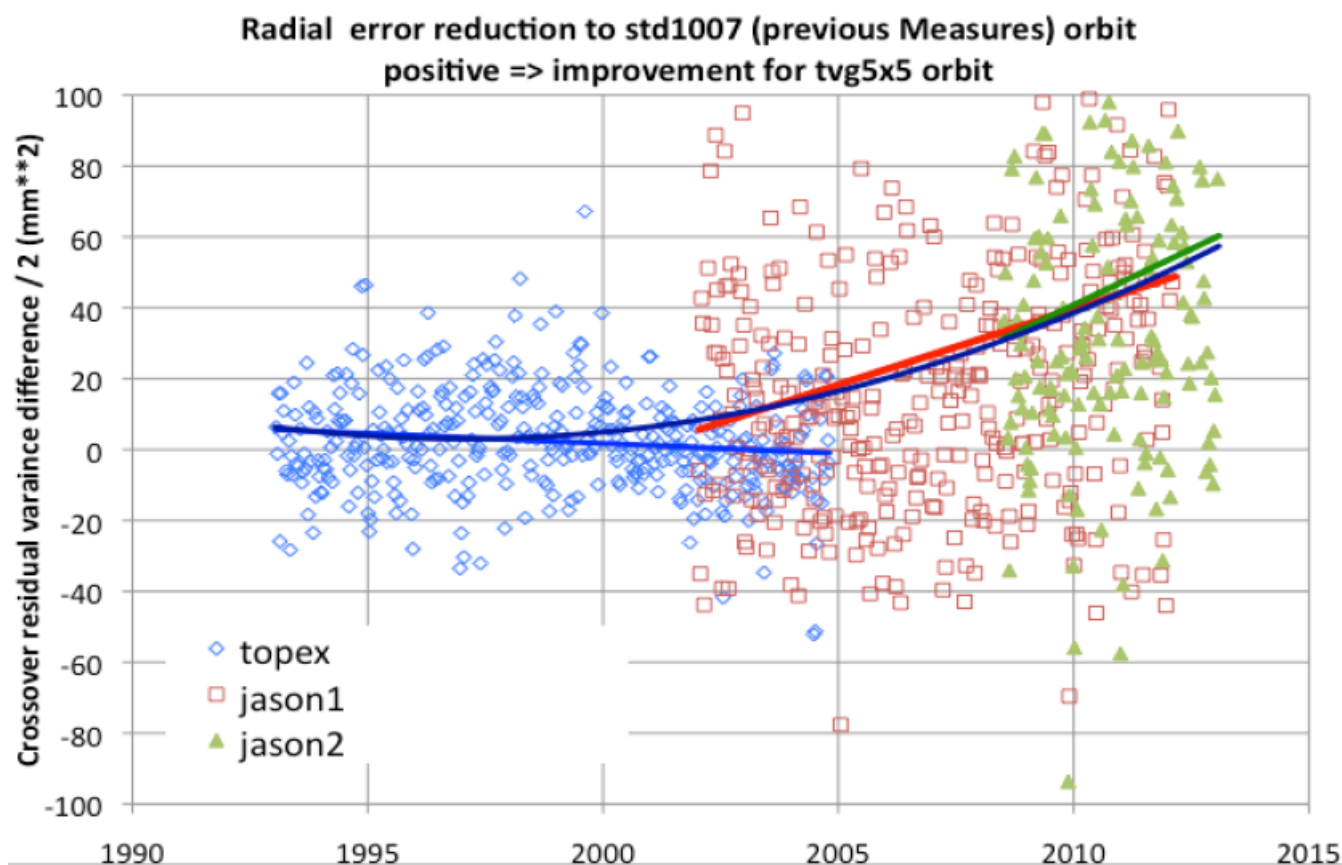


Version	Time-Variable Gravity	SLR Average RMS (cm)	Xover Average RMS (cm)
std1007	EIGEN-GL04S (rate terms in C20, C21, S21, C30 ,C40 only)	1.820	5.611
std1204	Harmonic fit SLR+DORIS solutions 1993-2012	---	---
+iers2010	(same as std1204)	1.817	5.604
tv5x5	SLR+DORIS-derived time series (1993-2012)	1.796	5.594

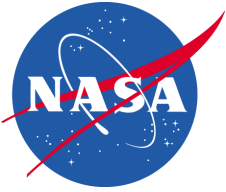
(Lemoine, F & Zelensky N et al. , October 2013, OSTST meeting, Boulder, Colorado)



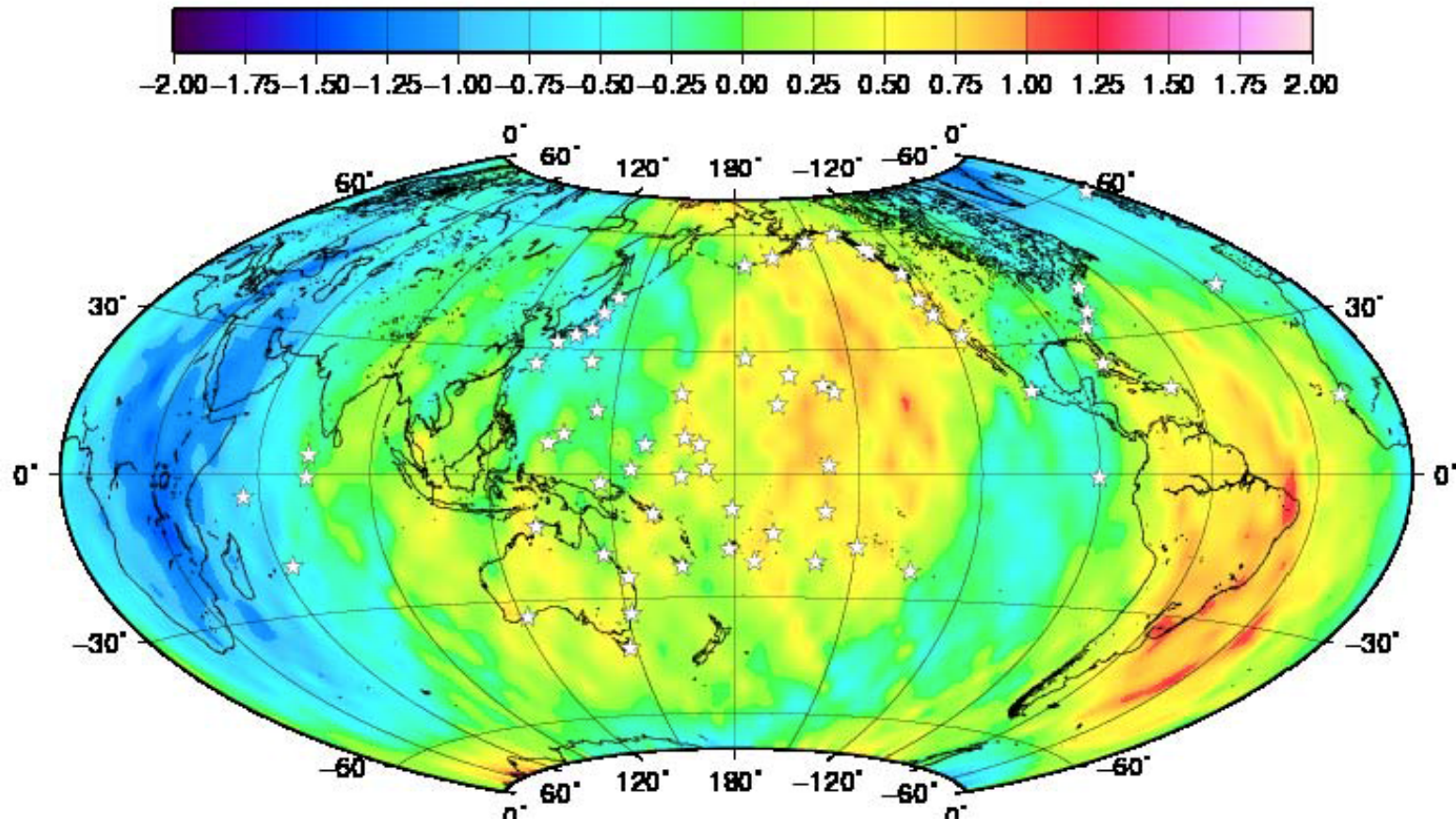
Impact on TP, Jason1, Jason2: Radial error Reduction from Xovers (Jan 1993 – ~May 2013) “EIGEN-GL04s” vs “time-series”



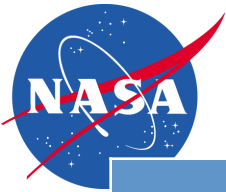
(Lemoine, F & Zelensky N et al. , October 2013, OSTST meeting, Boulder, Colorado)



**Jason2:
Radial Orbit Difference Rates (mm/yr),
July 2008 – Feb. 2013:
JPL11a vs. NASA GSFC TVG5x5**



(Lemoine, F & Zelensky N et al. , October 2013, OSTST meeting, Boulder, Colorado)

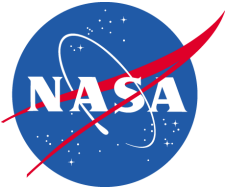


Atmospheric Gravity (1)



ECMWF-6hr (Description)

- Provided by Jean-Paul Boy (University of Strasbourg) for external users (email: jpboy@eost.u-strasbg.fr).
 - Files consist of C_{lm} and S_{lm} representing atmospheric gravity variations every six hrs.
 - <http://loading.u-strasbg.fr/V1.0/AGRA/>
 - Inverted Barometer Response is assumed for the oceans. S1 and S2 model of the atmospheric tides have been removed from the surface pressure fields before computing the Stokes coefficients – so the S1, S2 air tides must be externally applied.
 - **CHOICES:**
 1. **ERAIn (ERA-Interim)** or a consistent new Reanalysis **available since 1989**. There are no jumps in the time series by construction, by acc. To JPB there are some biases in the annual pressure variations compared to the operational model).
 2. **OPERA(Operational): Available from 2000 to the present**. The atmospheric field time series can have jumps due to changes in the operational model, but JPB removes these by doing fitting the differences between the operational versions before and after any model changes.
 3. **ERA40:** Old reanalysis, (**available 1970-2001**).
- > AT NASA GSFC we have used ERA40 (1993-2001) + then the Operational Series.

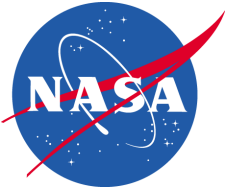


Atmospheric Gravity (2)

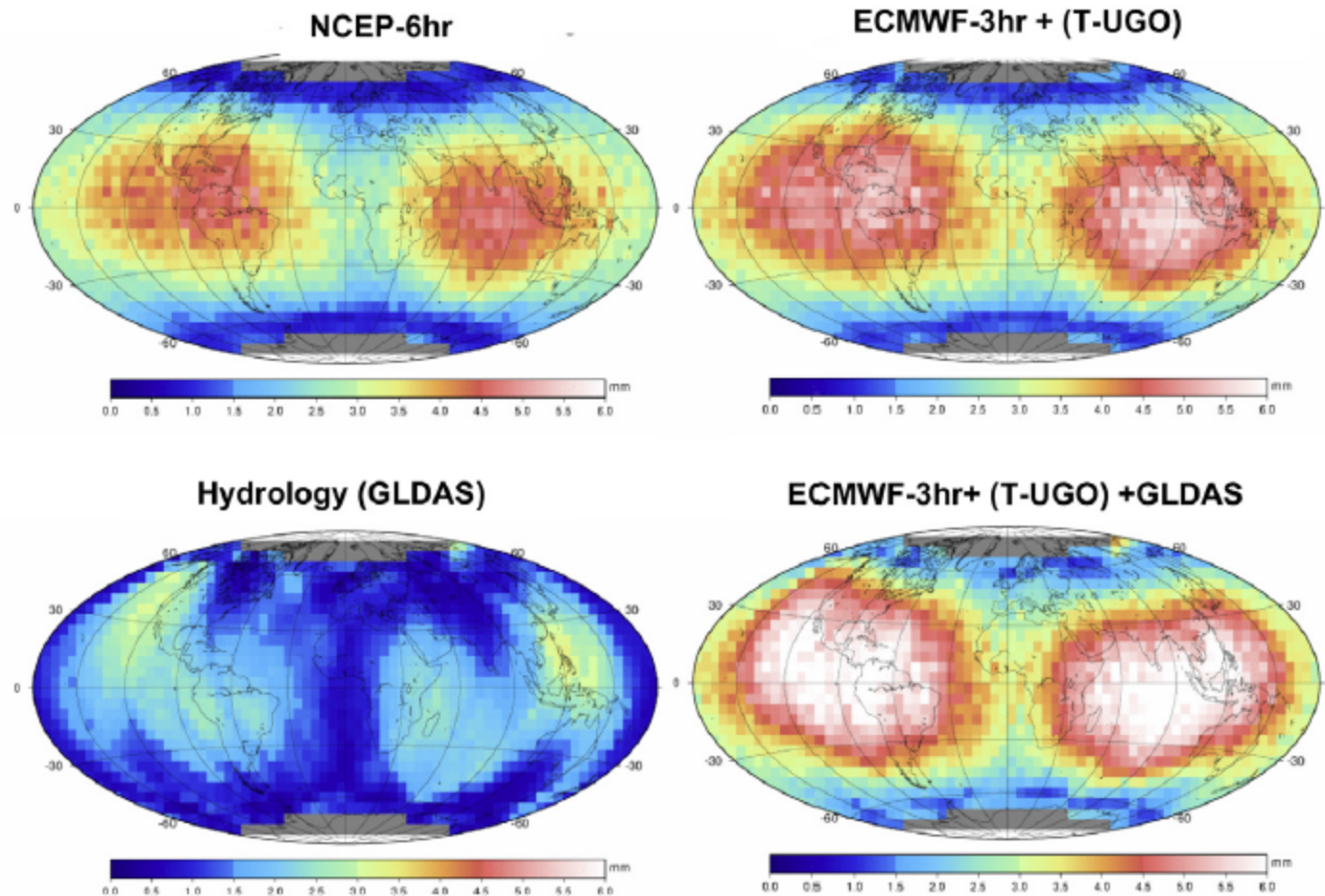


NCEP-6hr (Description)

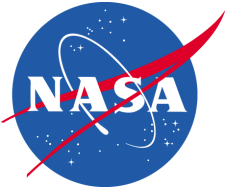
- Provided by automatic cron job. Developed by Leonid Petrov but maintained now by Dan Macmillan (VLBI group, NASA GSFC).
- Files consist of C_{lm} and S_{lm} representing atmospheric gravity variations every six hrs.
- <http://gemini.gsfc.nasa.gov/agra>
- Inverted Barometer Response is assumed for the oceans. S1 and S2 model of the atmospheric tides have been removed from the surface pressure fields before computing the Stokes coefficients – so the S1, S2 air tides must be externally applied.
- This NCEP/AGRA series is used by the CNES in the operational GDR production (Cerri et al., 2010).



Atmospheric Gravity: (3) Impact on Jason-1 Orbit, RMS Radial Orbit Differences (mm)



(Lemoine et al., 2010, Adv. Space Res., Figure 6)

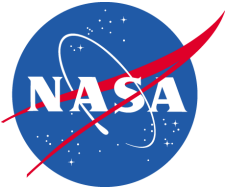


Time-Variable Gravity: IDS Reprocessing for ITRF2013 (1)

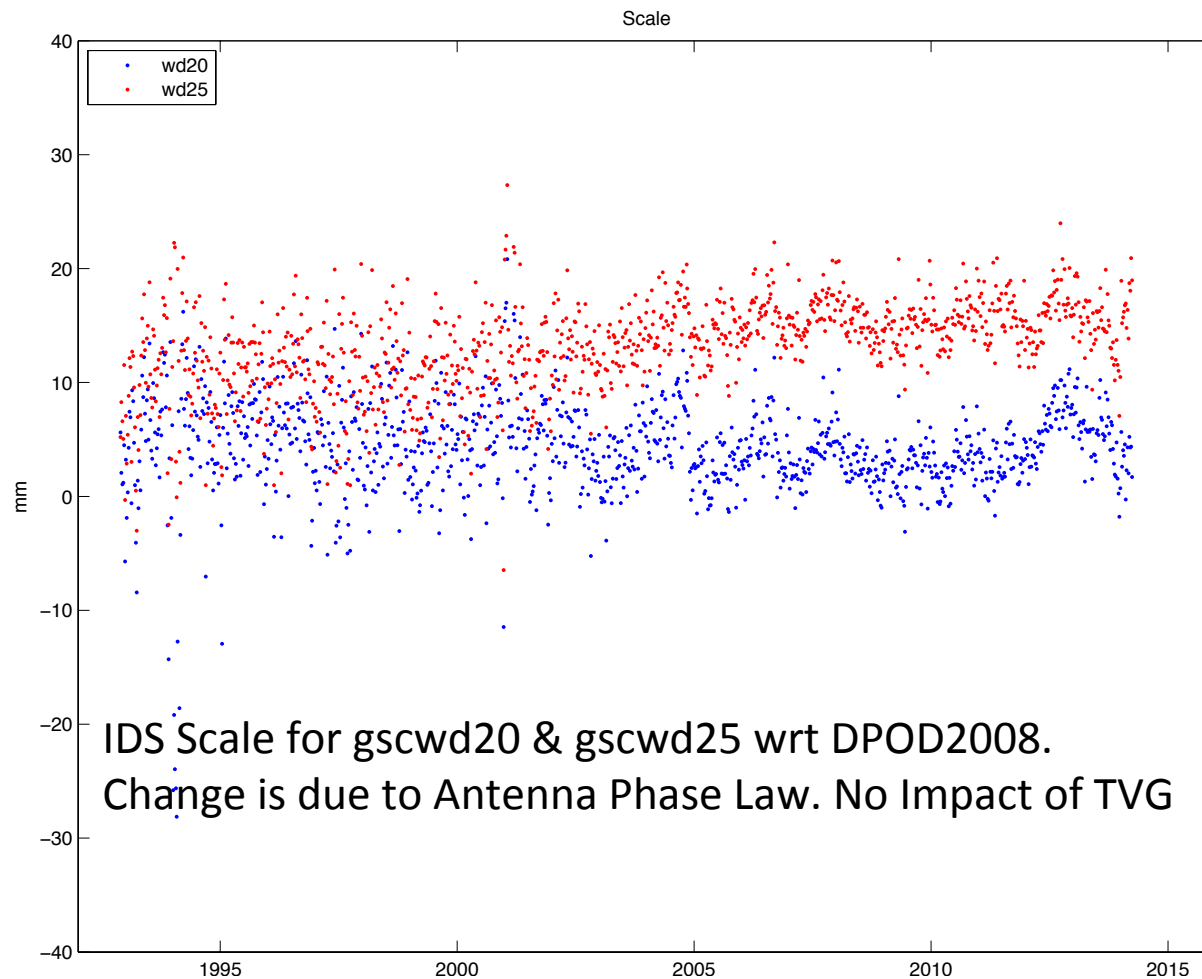


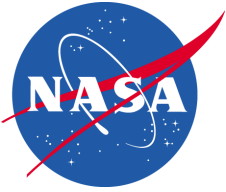
Analysis Centers adopted the following models:

1. ESA, GOP, IGN, LCA → EIGEN-6S2
2. GSC → NASA GSFC SLR+DORIS derived time series, + GRACE annual (L=6-20)
3. INA → harmonic fit to 1993-2012 time series to 4x4, + GRACE annual (L=5,20)

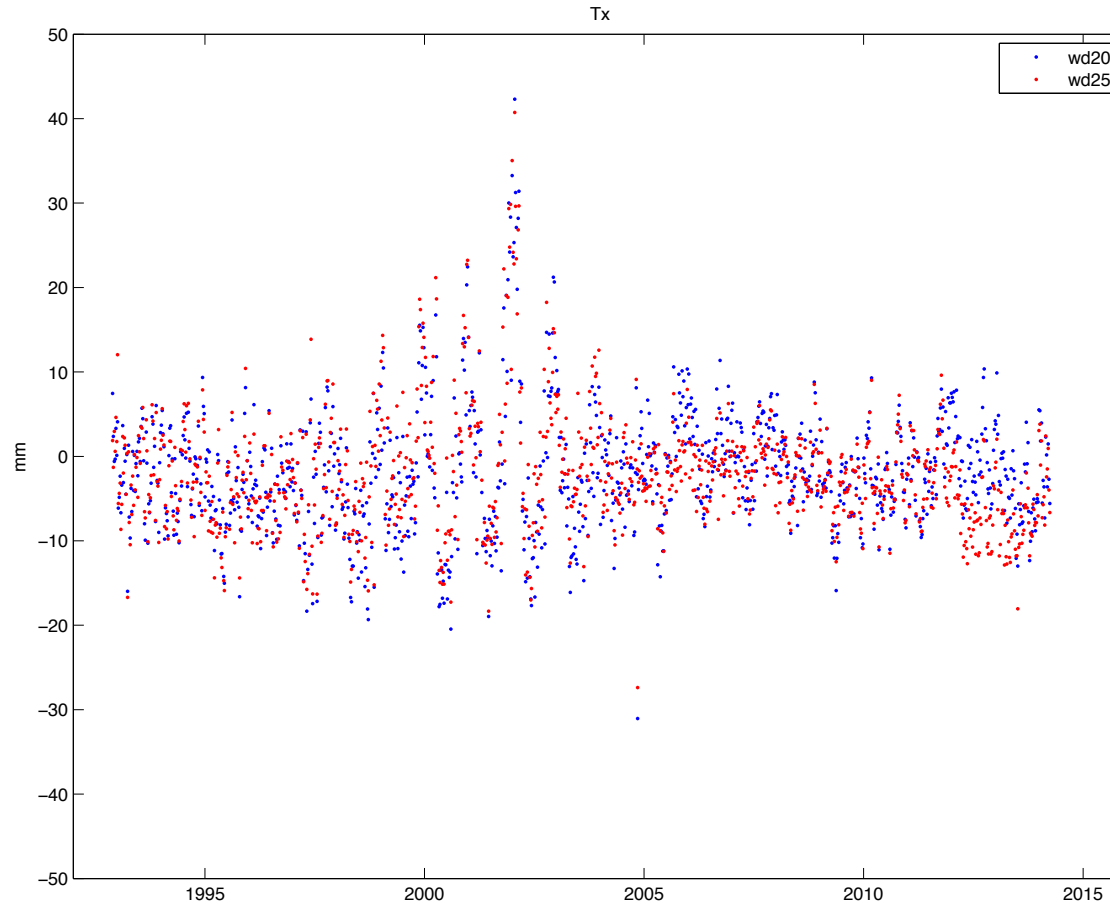


Time-Variable Gravity: IDS Reprocessing for ITRF2013 (2) Scale (gscwd20 vs gscwd25)

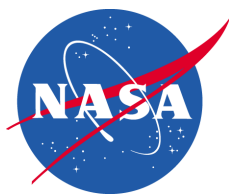




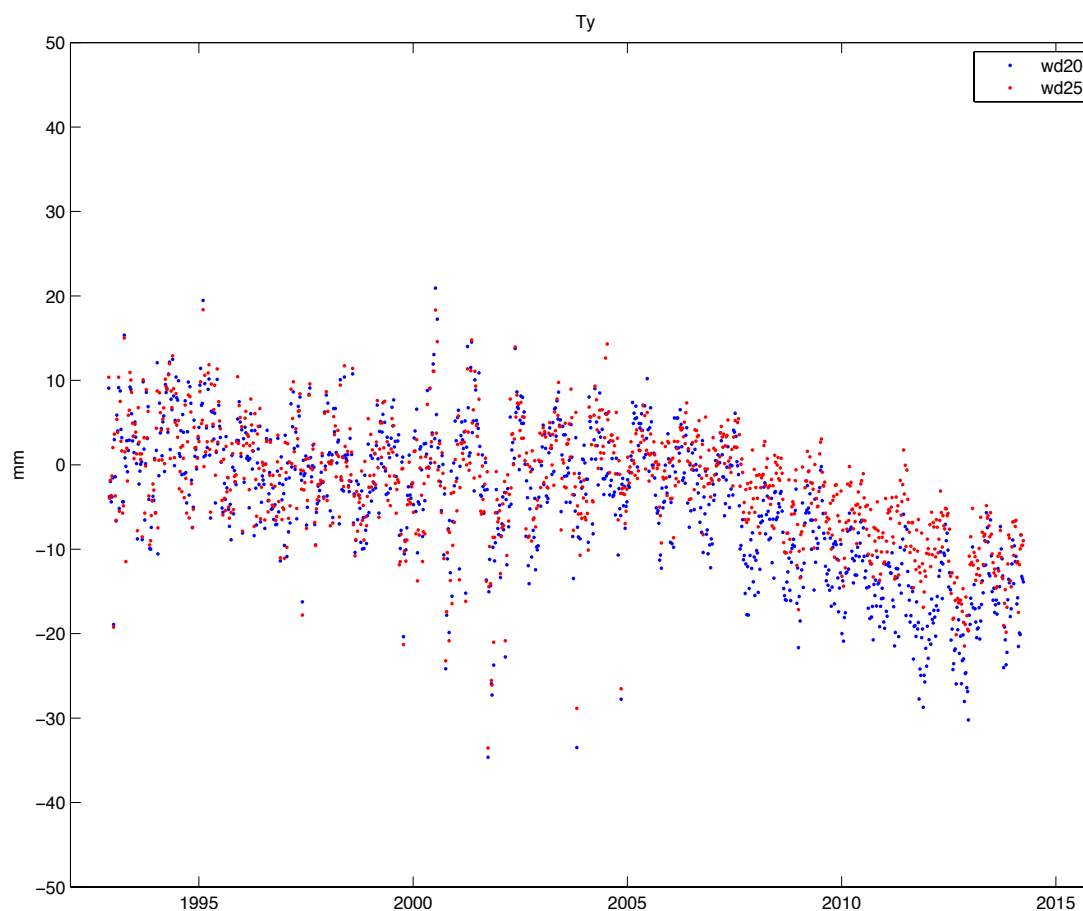
Time-Variable Gravity: IDS Reprocessing for ITRF2013 (2) Tx (gscwd20 vs gscwd25)



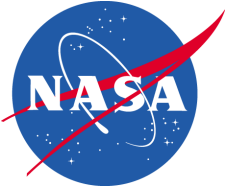
More detailed TVG modelling affects Tx & Ty. Seen also for other IDS AC contributions.



Time-Variable Gravity: IDS Reprocessing for ITRF2013 (3) Ty (gscwd20 vs gscwd25)



More detailed TVG modelling affects Tx & Ty. Seen also for other IDS AC contributions.



Thank you for your attention

Acknowledgements:

**Luca Cerri (CNES), Doug Chinn (SGT@NASA GSFC),
Alexandre Couhert (CNES), Nikita Zelensky (SGT@NASA GSFC)**