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Cartography and Geodesy

SLR and the Gravity Field

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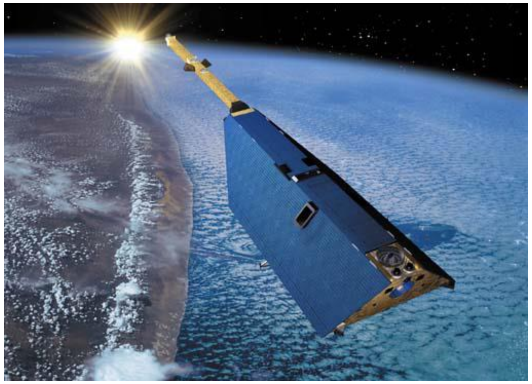
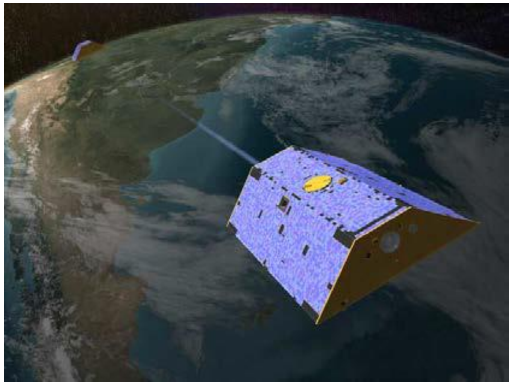
Gravity Field Determination

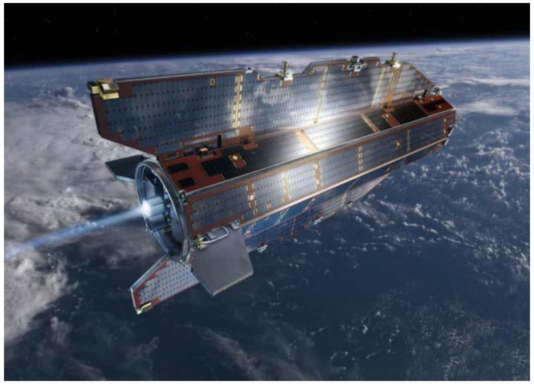
Dedicated gravity field satellite missions are available since several years



CHAMP



GRACE



GOCE

- **Why using SLR?**
  - Bad/unrealiable values of low-degree coefficients from GRACE: esp. C_{20}
  - Gravity field variations priori to the launch of CHAMP, GRACE etc.
  - Gravity field variations for the months with missing GRACE (K-Band) observations
  - Filling the gaps if no dedicated gravity field mission is in operation, e.g., between GRACE and GRACE-FO

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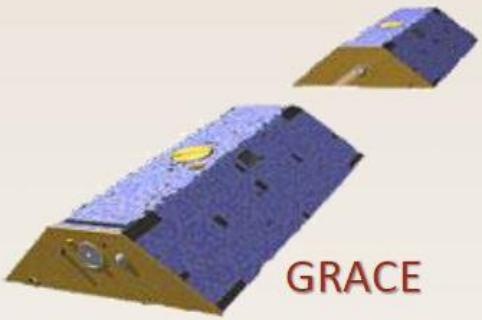
Gravity Field Determination and SLR

- SLR geodetic satellites (spherical satellites) orbit the Earth at higher altitudes than the satellite gravity missions (CHAMP, GRACE, GOCE etc.)
  - Lower sensitivity
- SLR observations are typically used for deriving
  - Low-degree gravity field coefficients (mainly degree 2)
  - Zonal harmonics
- Higher-degree monthly gravity field models can also be well derived from SLR observations using a combination of long and short arcs

GRACE vs. SLR



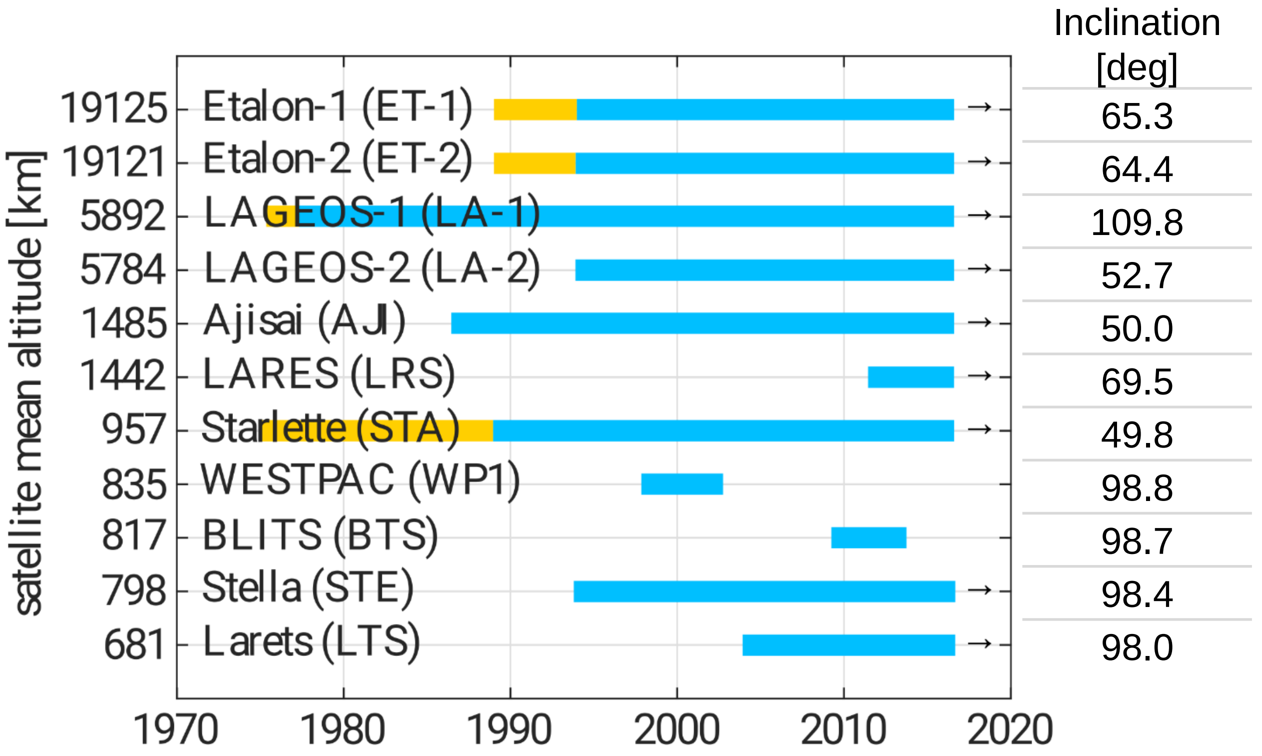
GRACE	SLR
Kinematic orbit solutions + K-band range and range rates	Dynamic approach
Microwave observations	Laser observations
Differential technique using (pseudo)ranges between satellites	Undifferentiated (direct) ranges between ground stations and satellites
∼1M observations per month	∼40k observations per month
High-rate observations	Normal points every 30 s (Starlette, Stella, AJISAI, LARES, Larets, BLITS) or every 120 s (LAGEOS)
Continuous observations	Noncontinuous observations limited by the station-satellite visibility
Homogeneous quality of observations	Quality of observations dependent on SLR stations (different frequencies and laser systems: 10Hz/kHz used)
Homogeneous distribution of observations	Most of tracking stations in the northern hemisphere
No weather dependency	Weather dependency on observations, + the Blue-Sky effect
Low and high-degree coefficients can be resolved	Typically only low-degree coefficients can be resolved
Reasonably small correlations between estimated parameters	Strong correlations between some harmonics resulting in the lumped coefficients
No direct link to reference frame	Directly connected to the terrestrial reference frame
Very low altitude of satellites ∼380 km	Different altitudes, typically above 800 km
The same inclination for both GRACE satellites	Different inclinations
Strong S_2 aliasing with orbits	Strong S_2 aliasing only for some satellites (e.g., Stella, Larets, Blits)
Very sensitive to non-gravitational forces (atmospheric drag, albedo, solar radiation)	Sensitivity to non-gravitational forces substantially reduced
Sensitive to ionosphere activity	No ionosphere delay of the signal
Active satellites, expensive maintenance	Passive, low-cost satellites
Limited life-time	Unlimited life-time

SLR Satellites: Sensitivity to Gravity Field

Perturbing accel.	Accel. on LAGEOS	Accel. on AJISAI	Accel. on LARES	Accel. on Stella
Gravitational perturbations:				
· Earth's monopole	2.7	6.4	6.5	7.7
· Earth's oblateness $C_{2\,0}$	$1.0 \cdot 10^{-3}$	$6.2 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$	$8.8 \cdot 10^{-3}$
· Low-order grav. $C_{2\,2}$	$6.0 \cdot 10^{-6}$	$3.6 \cdot 10^{-5}$	$3.7 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$
· Low-order grav. $C_{6\,6}$	$8.6 \cdot 10^{-8}$	$3.1 \cdot 10^{-6}$	$3.2 \cdot 10^{-6}$	$6.3 \cdot 10^{-6}$
· Mid-order grav. $C_{20\,20}$	$8.1 \cdot 10^{-13}$	$1.5 \cdot 10^{-8}$	$1.6 \cdot 10^{-8}$	$1.1 \cdot 10^{-7}$
· Grav. attr. of Moon	$2.1 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$
· Grav. attr. of Sun	$9.6 \cdot 10^{-7}$	$6.4 \cdot 10^{-7}$	$6.5 \cdot 10^{-7}$	$5.7 \cdot 10^{-7}$
· Grav. attr. of Venus	$1.3 \cdot 10^{-10}$	$8.5 \cdot 10^{-11}$	$8.5 \cdot 10^{-11}$	$7.8 \cdot 10^{-11}$
· Solid Earth tides	$3.7 \cdot 10^{-6}$	$2.0 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$
· Ocean tides	$3.7 \cdot 10^{-7}$	$1.9 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$3.0 \cdot 10^{-6}$
General relativity:				
· Schwarzschild effect	$2.8 \cdot 10^{-9}$	$1.1 \cdot 10^{-8}$	$1.1 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$
· Lense-Thirring effect	$2.7 \cdot 10^{-11}$	$1.3 \cdot 10^{-10}$	$1.4 \cdot 10^{-10}$	$1.8 \cdot 10^{-10}$
· Geodetic precession	$3.4 \cdot 10^{-11}$	$4.2 \cdot 10^{-11}$	$4.2 \cdot 10^{-11}$	$4.3 \cdot 10^{-11}$
Non-gravitational perturbations:				
· Solar radiation pressure	$3.5 \cdot 10^{-9}$	$2.5 \cdot 10^{-8}$	$1.1 \cdot 10^{-9}$	$4.4 \cdot 10^{-9}$
· Earth radiation pressure	$4.4 \cdot 10^{-10}$	$8.6 \cdot 10^{-9}$	$3.9 \cdot 10^{-10}$	$1.8 \cdot 10^{-9}$
· Thermal re-radiation	$5.0 \cdot 10^{-11}$	$4.1 \cdot 10^{-10}$	$1.9 \cdot 10^{-11}$	$6.9 \cdot 10^{-11}$
· Light aberration	$1.1 \cdot 10^{-13}$	$1.1 \cdot 10^{-12}$	$5.1 \cdot 10^{-14}$	$2.0 \cdot 10^{-13}$
· Atmospheric drag ($\sim$ min)	$0.8 \cdot 10^{-14}$	$3.0 \cdot 10^{-11}$	$2.6 \cdot 10^{-12}$	$5.0 \cdot 10^{-11}$
· Atmospheric drag ($\sim$ max)	$2.0 \cdot 10^{-13}$	$5.9 \cdot 10^{-10}$	$4.8 \cdot 10^{-11}$	$5.0 \cdot 10^{-8}$

Sensitivity shows clear dependency on orbital height

SLR Satellites: Sensitivity to Gravity Field



Current ILRS standard setup

BUT:
Satellites with lower altitudes are needed for gravity field determination

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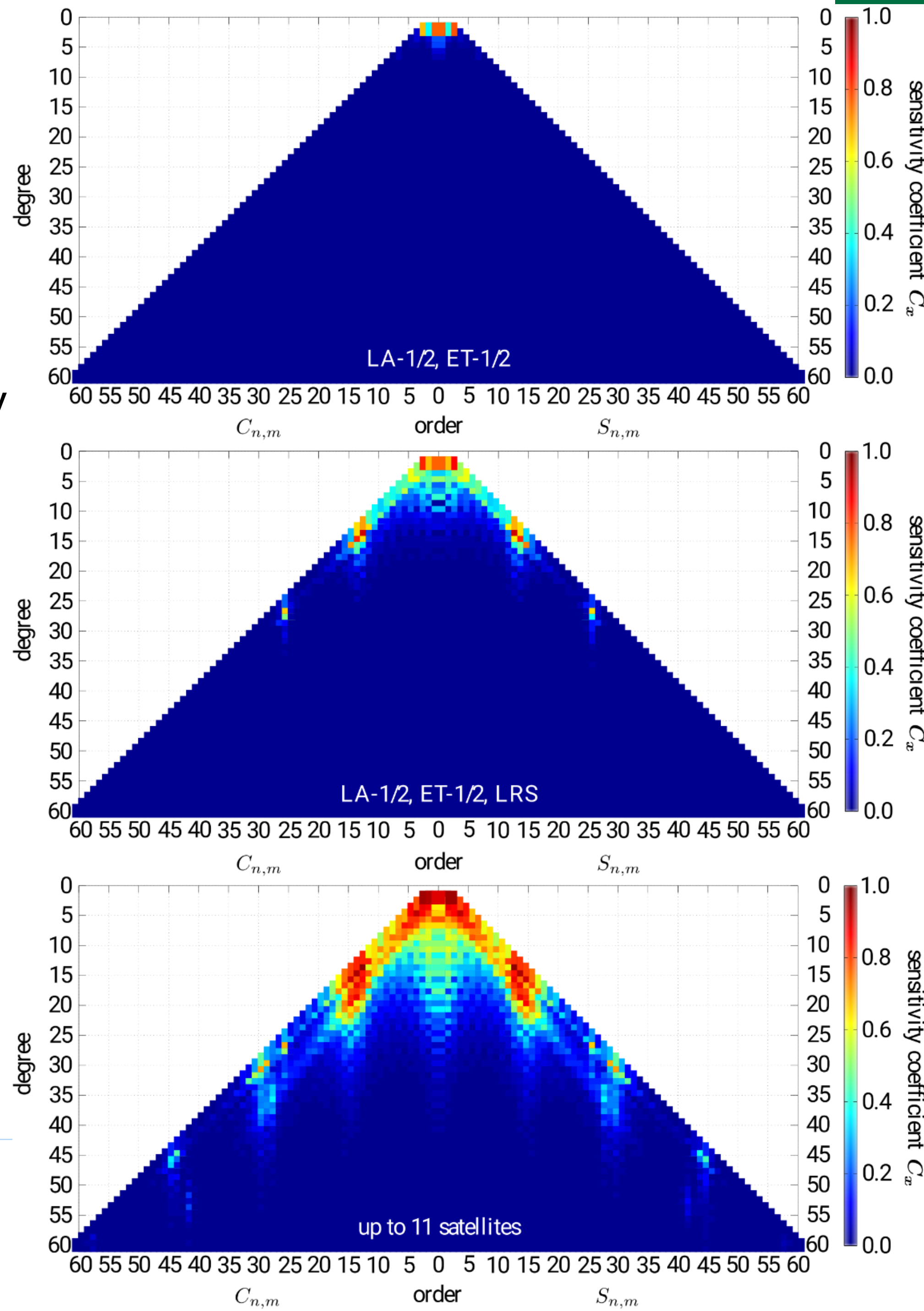
SLR Satellites: Sensitivity to Gravity Field

With an increased number of used satellites, the solution gains sensitivity w.r.t. the Earth's gravity field:

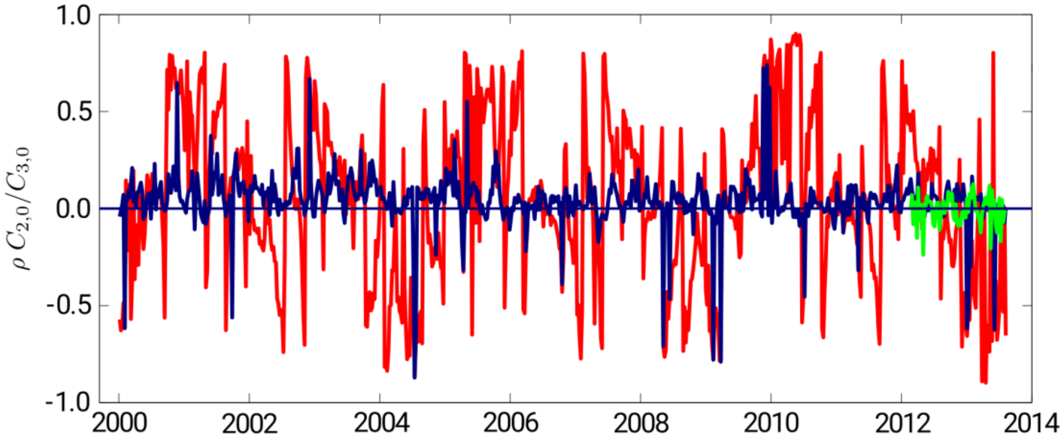
- 4 satellites: up to d/o 3
- 5 satellites: up to d/o 6 (higher d/o for tesseral coefficients)
- Max. constellation: up to d/o 12

But:

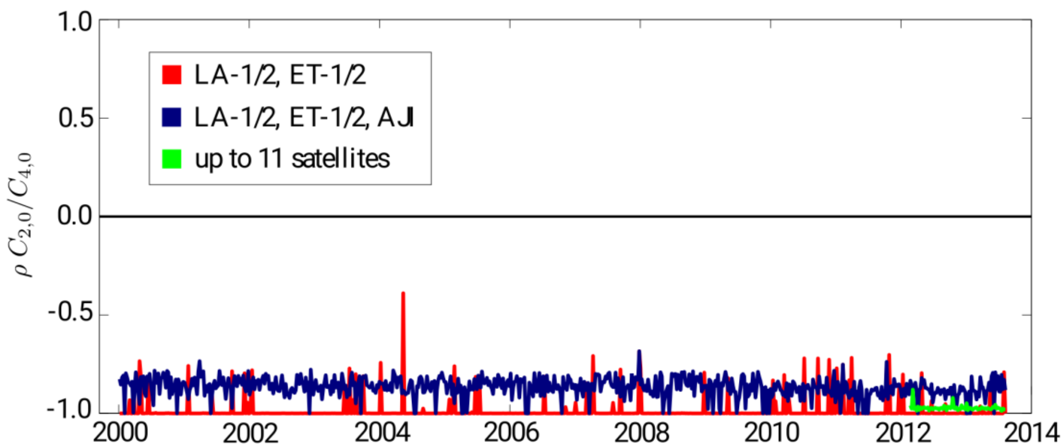
- Not all coefficients can be determined reliably due to remaining correlations!



SLR Satellites: Correlations between Gravity Field Coefficients



- The correlation between $C_{2,0}$ and $C_{3,0}$ can be reduced significantly by using additional satellites.
- In an 11-satellite constellation, both parameters are decorrelated.



- The correlation between $C_{2,0}$ and $C_{4,0}$ cannot be eliminated.
- Reason: there is no satellite orbit sensitive to only one of these coefficients (geometrical correlation of both coefficients).

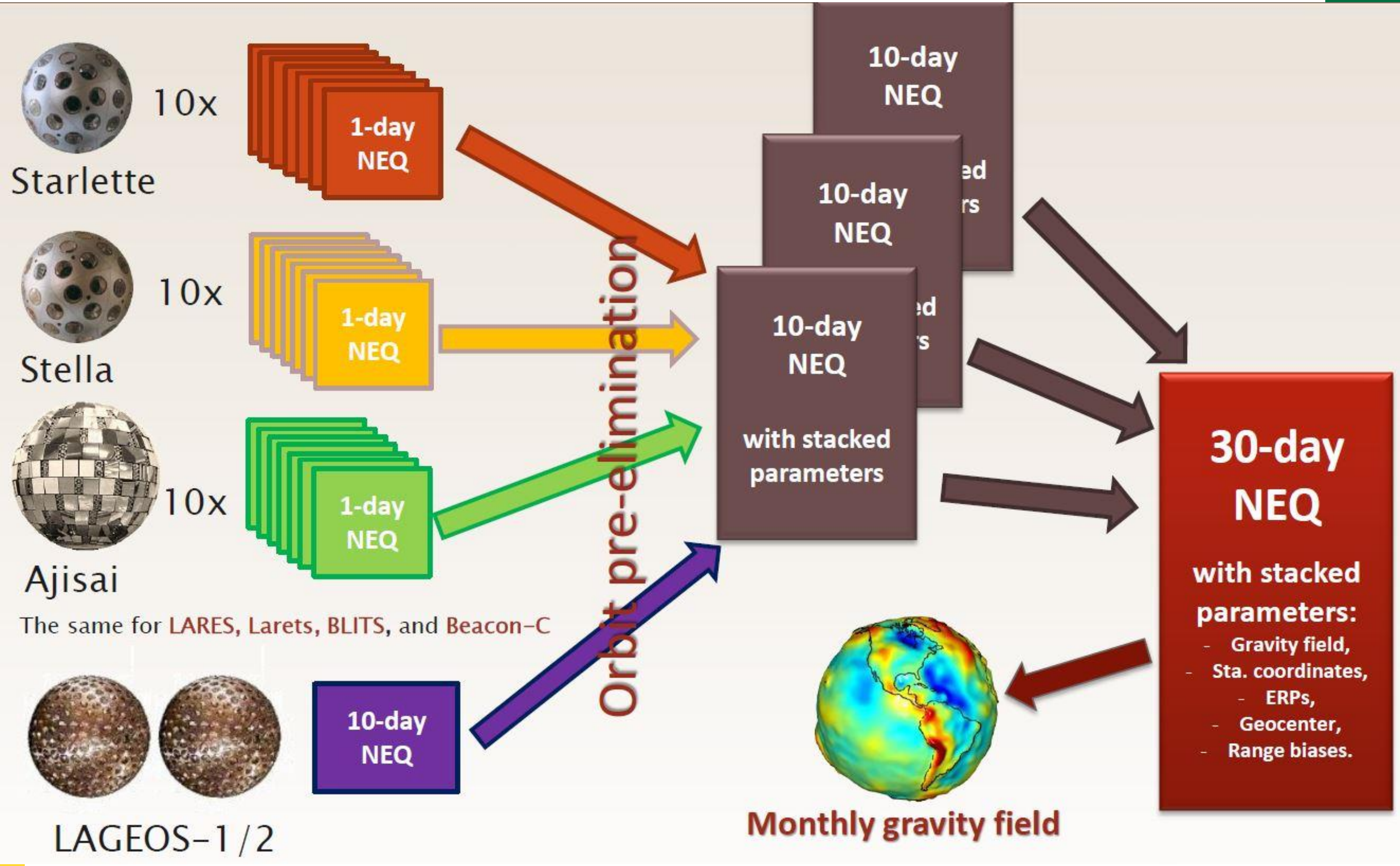
SLR gravity solutions: Parameter set-up

Estimated parameters		SLR solutions
		LAGEOS-1/2, Starlette, Stella, AJISAI, LARES, Blits, Larets, Beacon-C
Orbits	Osculating elements	a, e, i, Ω, ω, u_0 (LAGEOS: 1 set per 10 days, LEO: 1 set per 1 day)
	Dynamical parameters	LAGEOS-1/2 : S_0, S_S, S_C (1 set per 10 days) Sta/Ste/AJI : C_D, S_C, S_S, W_C, W_S (1 set per day)
	Pseudo-stochastic pulses	LAGEOS-1/2 : no pulses Sta/Ste/AJI : once-per-revolution in along-track only
Earth rotation parameters		X_P, Y_P, UT1-UTC (Piecewise linear, 1 set per day)
Geocenter coordinates		1 set per 30 days
Earth gravity field		**Estimated up to d/o 10/10** (1 set per 30 days)
Station coordinates		1 set per 30 days
Other parameters		Range biases for all stations (LEO) and for selected stations (LAGEOS)

Here:
Set-up of the solutions from AIUB using the Bernese GNSS Software

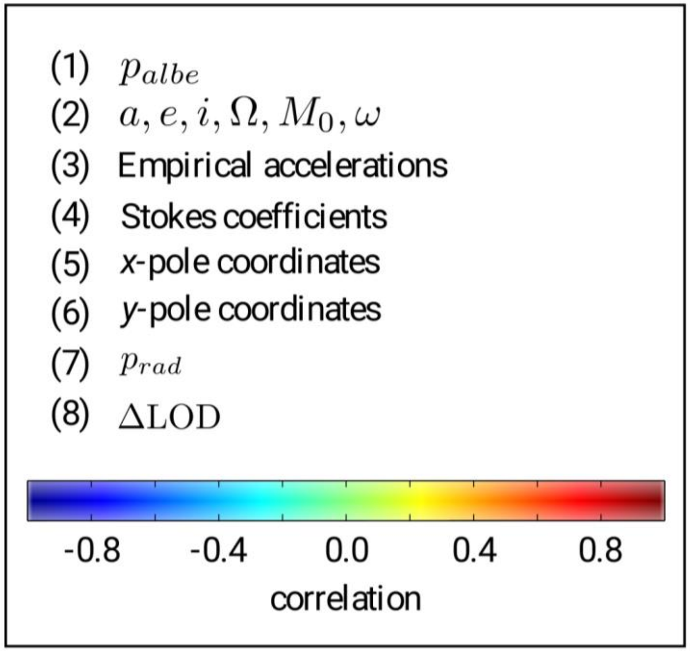
Similar solutions available from DGFI-TUM with up to 11 satellites using DOGS

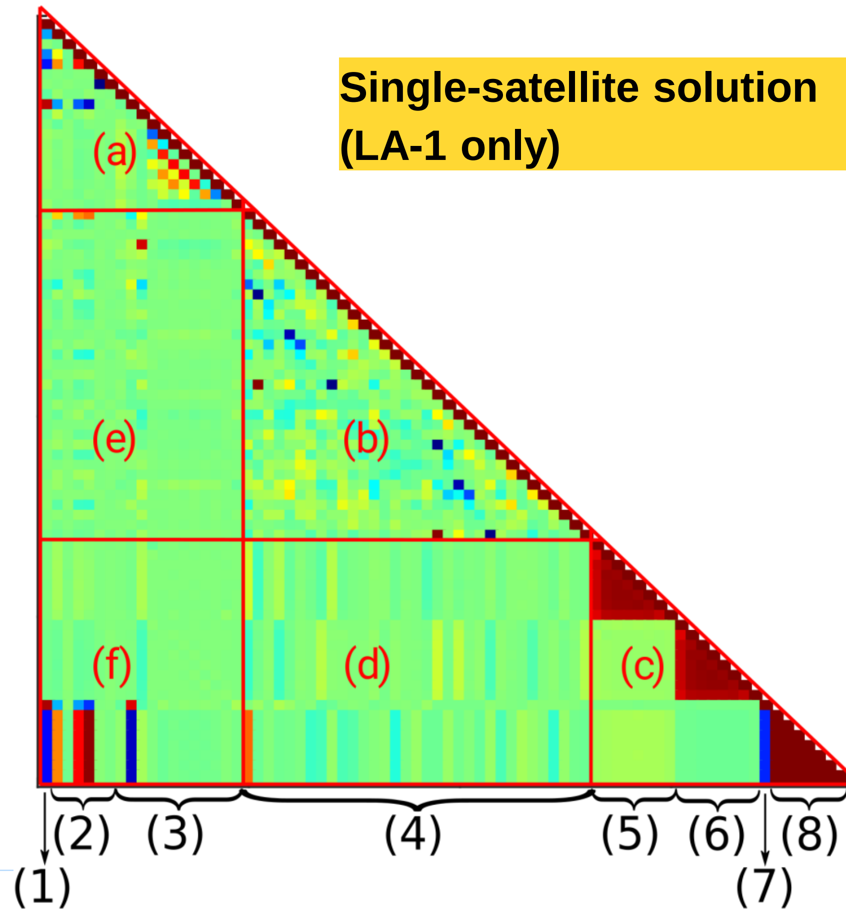
SLR gravity solutions (Bernese GNSS Software)



Selection of satellites: Correlations between parameters

Correlation matrix of combined solution comprising orbit parameters (LA-1 only), GFC and EOP





(a) orbital elements and p_{albe}

(b) Stokes coefficients

(c) EOP and SRP scaling factor (p_{rad})

(d), (e), (f) correlations between parameter groups

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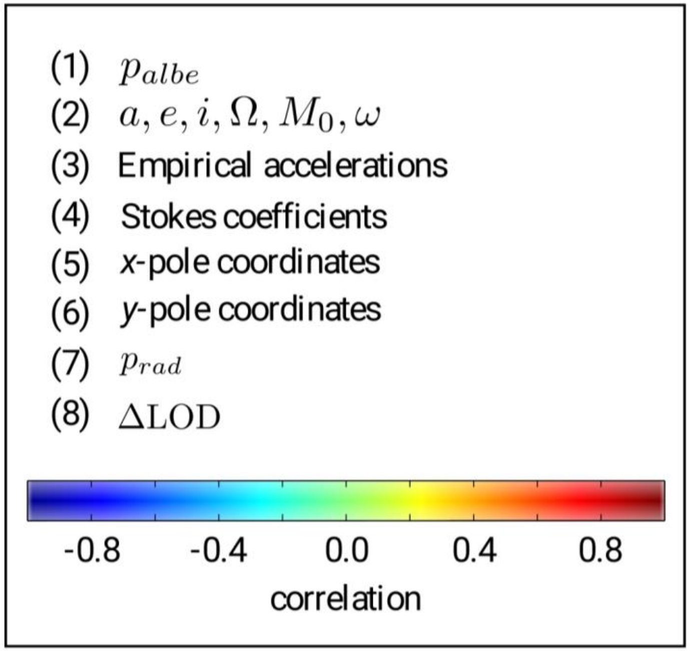

- (a) orbital elements and p_{albe}
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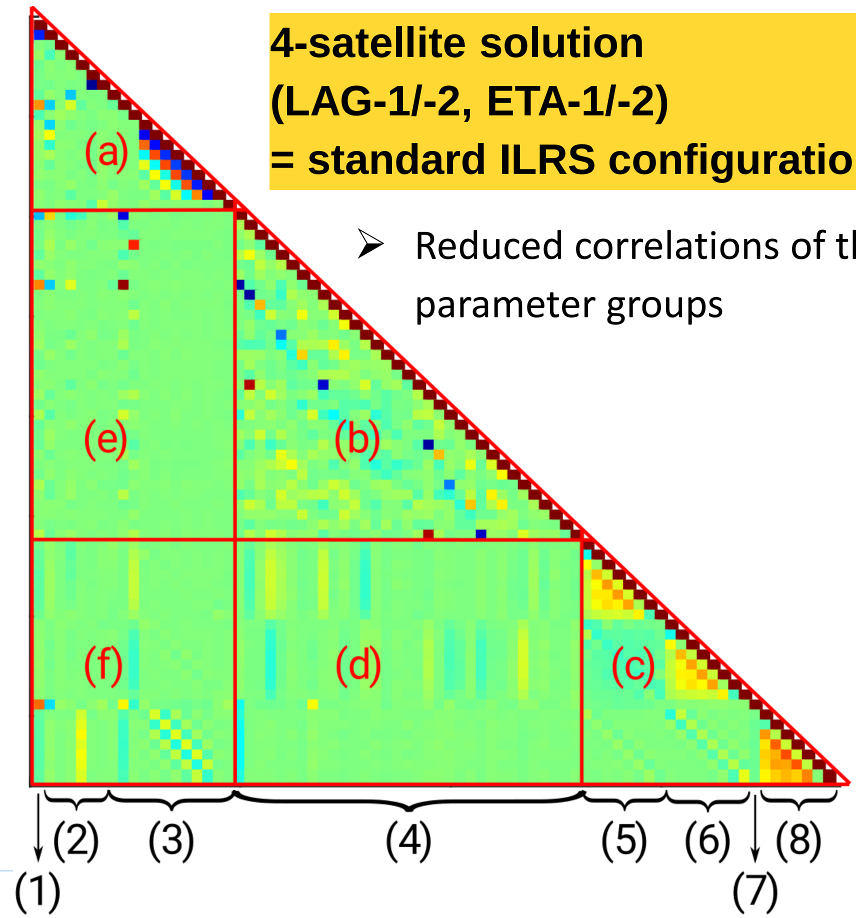

4-satellite solution
(LAG-1/-2, ETA-1/-2)
= standard ILRS configuration

- ➢ Reduced correlations of the parameter groups

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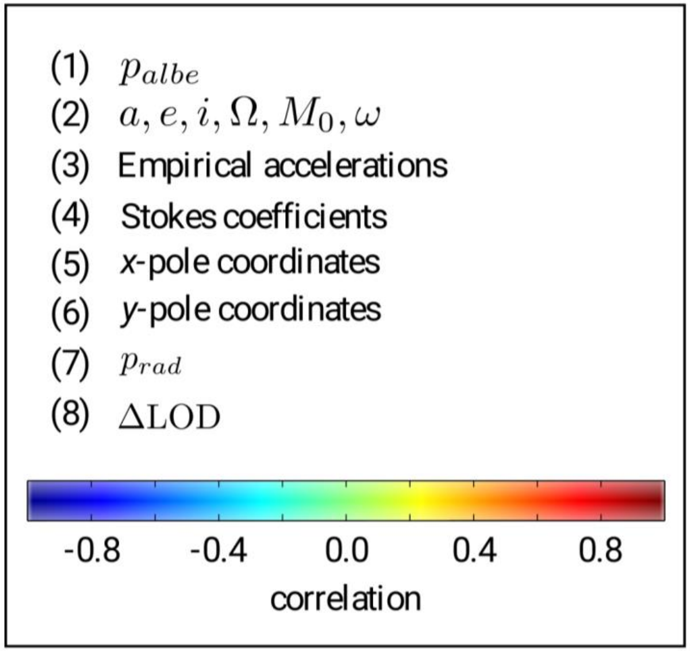
Selection of satellites: Correlations between parameters

Correlation matrix of combined solution comprising orbit parameters (LA-1 only), GFC and EOP



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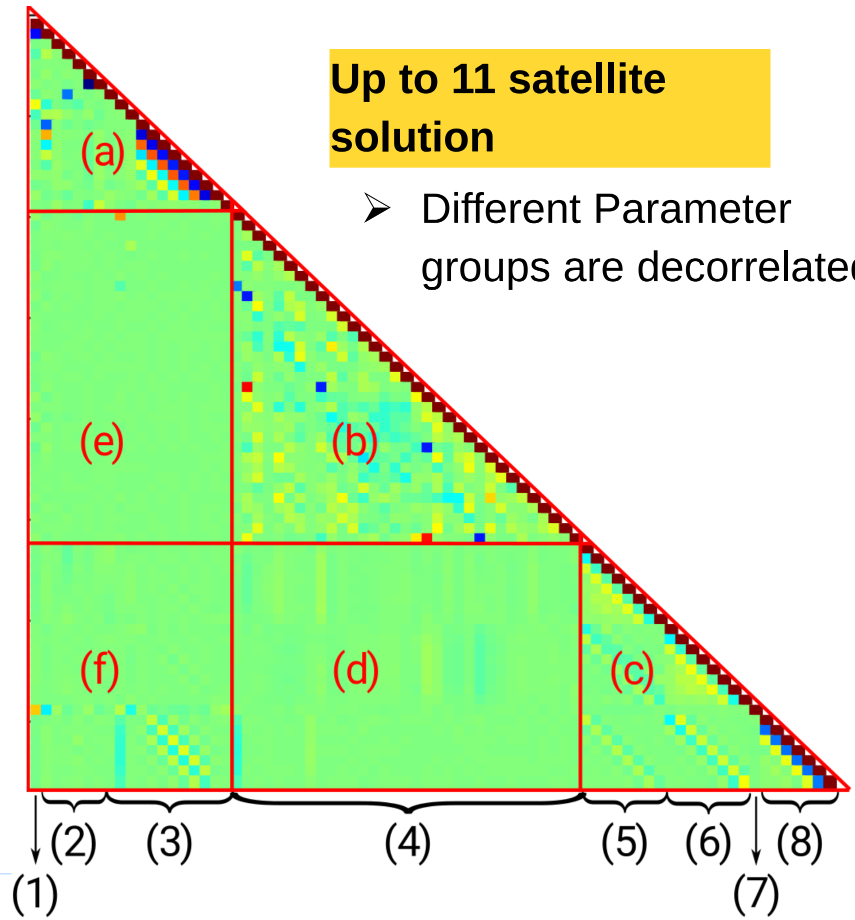

Up to 11 satellite solution

- Different Parameter groups are decorrelated

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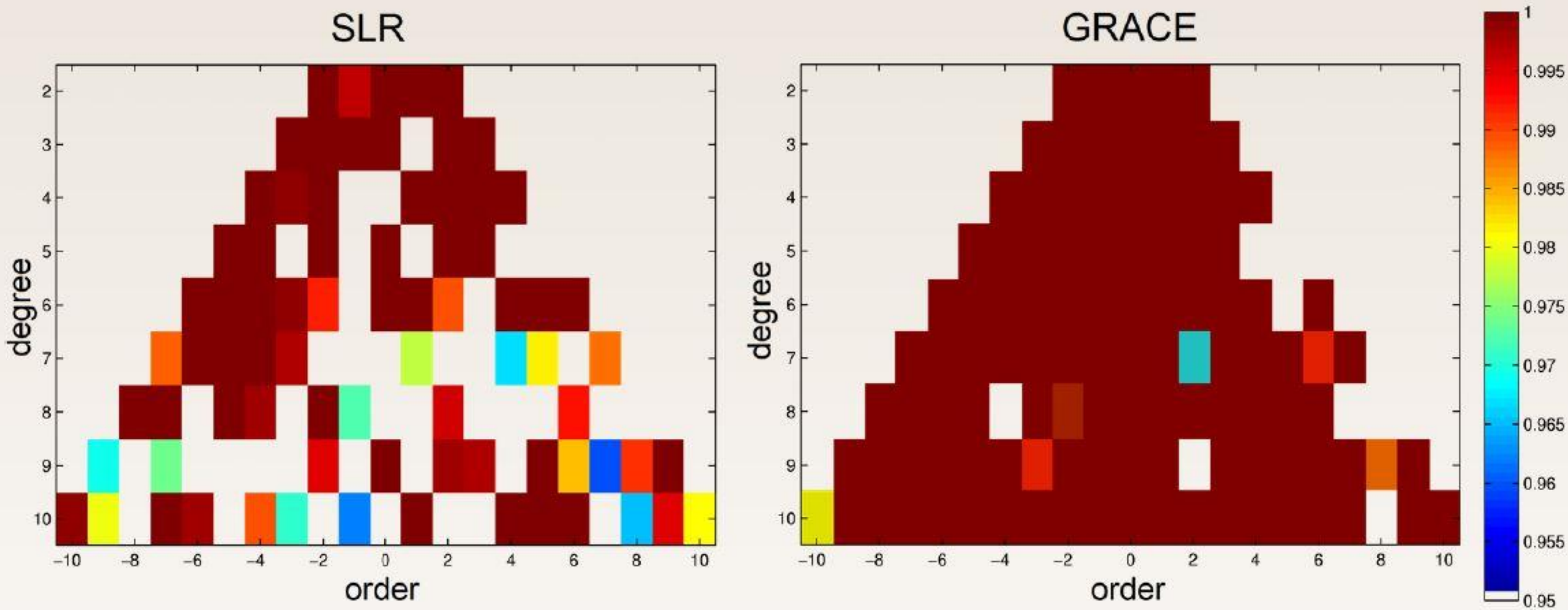
SLR gravity solutions: Comparison with GRACE Annual signal



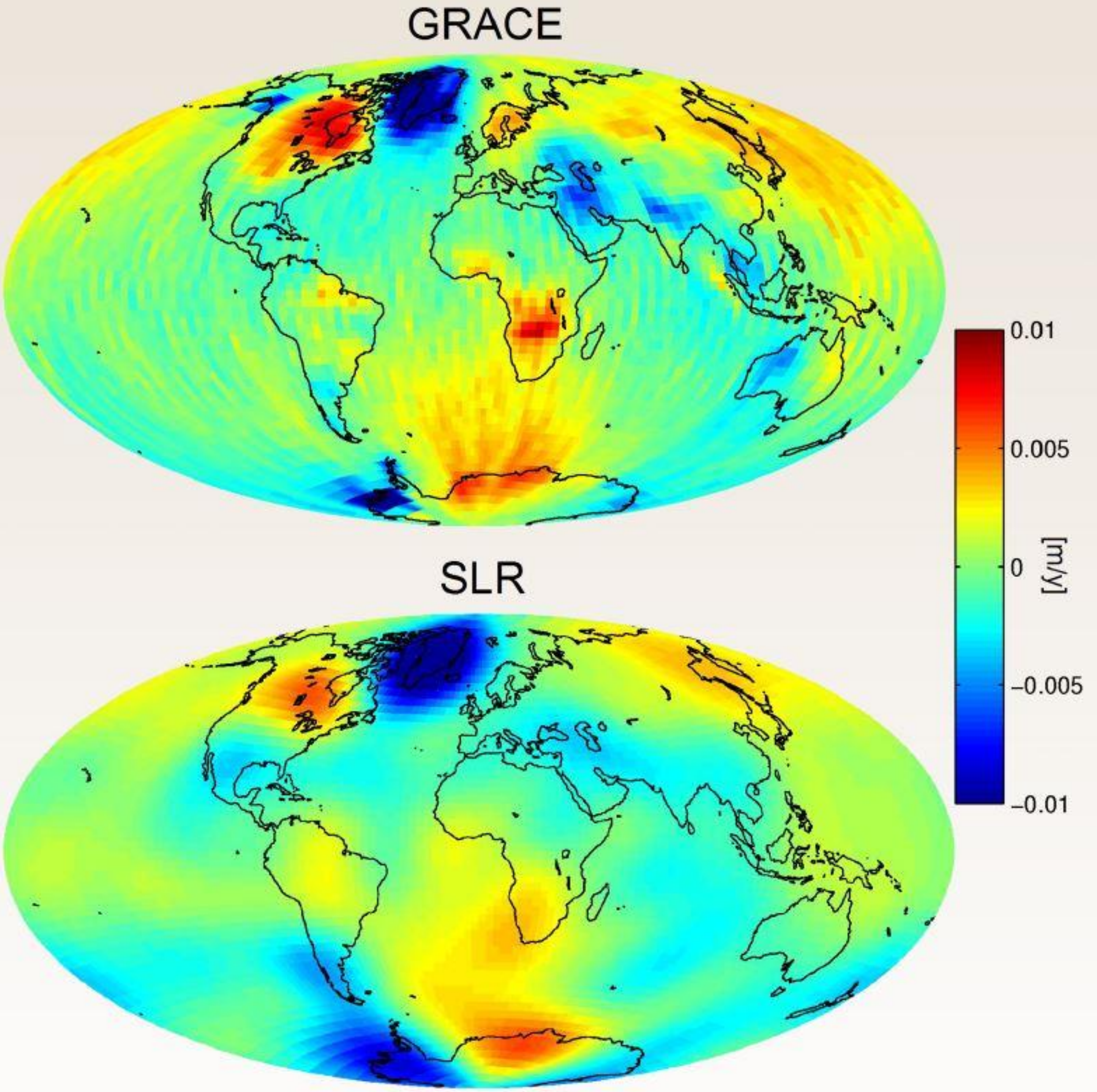
Associated cumulative distribution function showing the significance of the recovered annual signal for SLR solutions (left) and GRACE solutions (right).

=> SLR mostly sensitive to d/o 6/6

SLR gravity solutions: Comparison with GRACE Secular changes

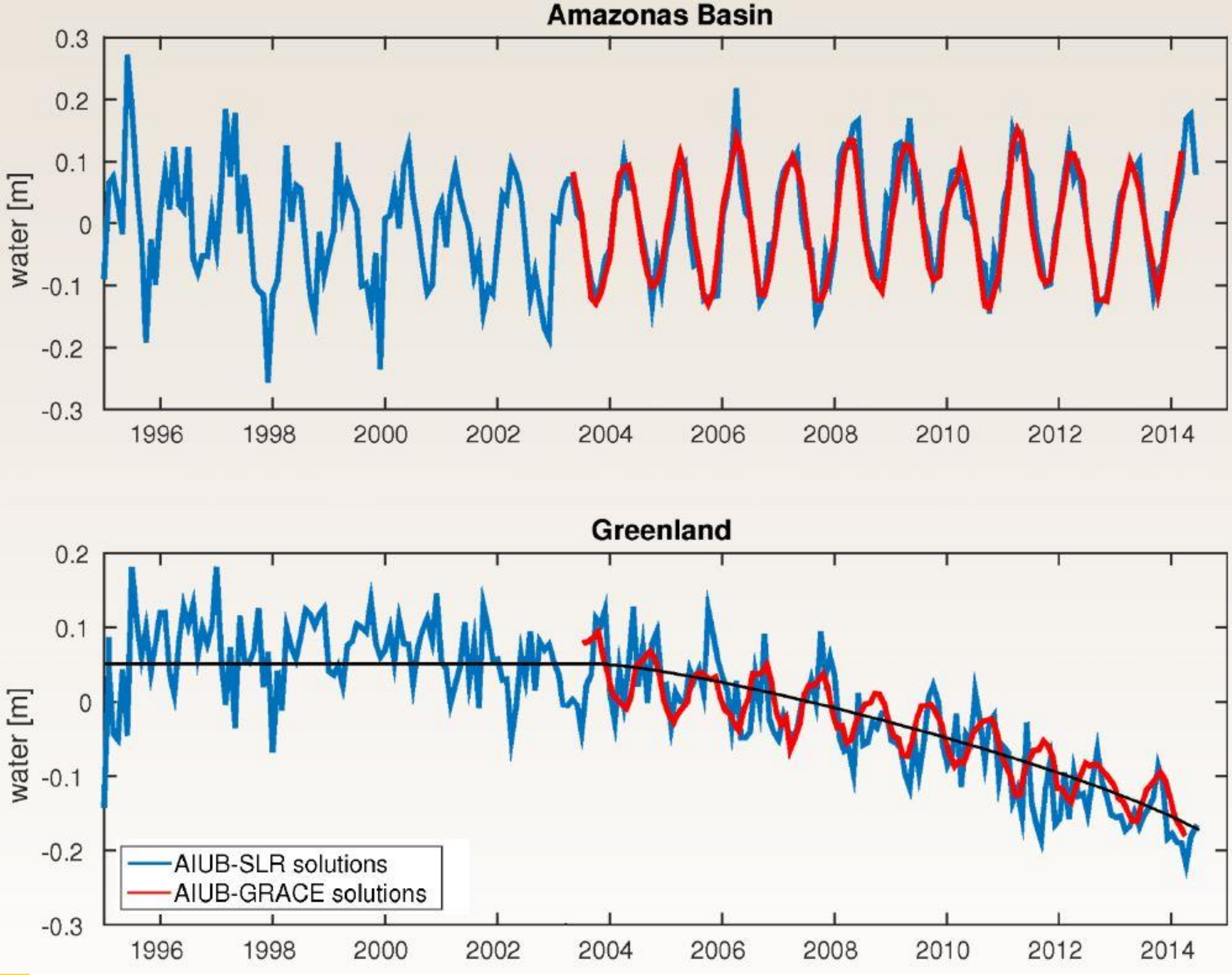
Secular changes of geoid deformations derived from SLR show a very high level of consistency with the GRACE-based results, however, with a lower spatial resolution.

The ice mass loss in Greenland, West Antarctica and Patagonia is well captured in the SLR solutions.



Reference: Sośnica, K., Jäggi, A., Meyer, U., Thaller, D., Beutler G., Arnold, D., Dach, R. (**2015**). *Time variable Earth's gravity field from SLR satellites*. **Journal of Geodesy,** on-line (http://link.springer.com/article/10.1007/s00190-015-0825-1)

SLR gravity solutions: Comparison with GRACE Mass change in individual regions



The SLR solutions can recover the largest seasonal and secular variations of the gravity field, which correspond to the large-scale mass transport in the system Earth, e.g., the accelerating ice mass depletion in Greenland.

The amplitudes in the SLR solutions up to d/o 10/10 are typically underestimated due to the limited sensitivity of SLR solutions to coefficients of degree 7-10.

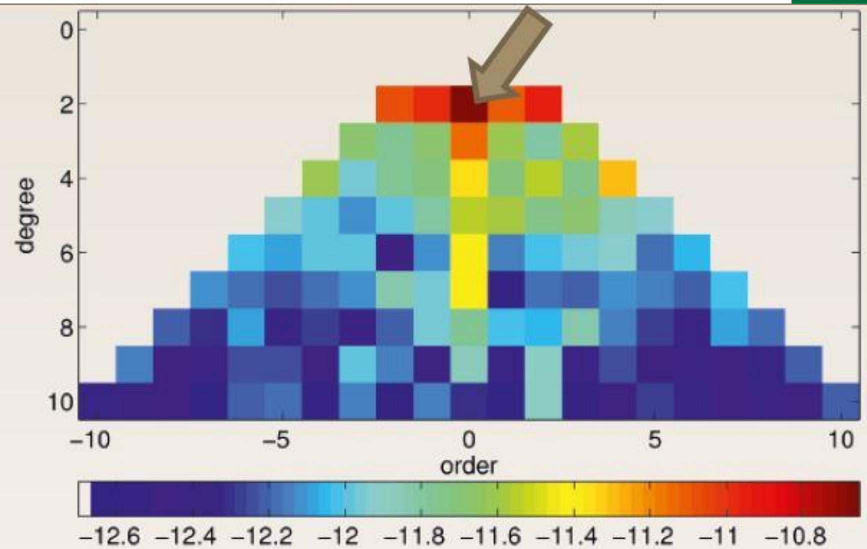
SLR + GRACE (GPS) + GRACE (K-Band)

Can SLR contribute anything at all?

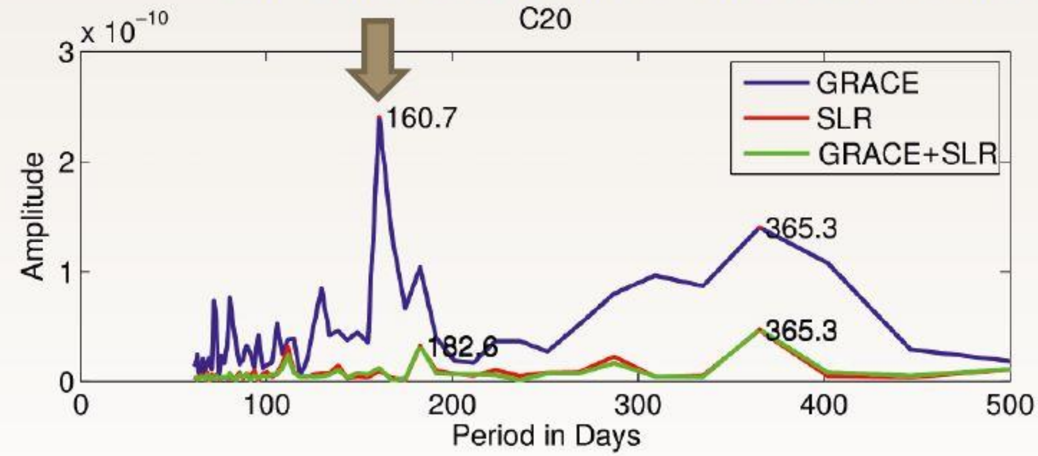
SLR contributes most to the zonal gravity field coefficients and the coefficients of degree-2.

C_{20} is degraded in the GRACE solutions due to long-period signals, because some signals in C_{20} have the same period as the S_2 and S_1 tidal aliases with GRACE orbits. This degradation is reflected in a large peak of 160 days in the C_{20} spectra.

Combination of GRACE with SLR solutions remarkably reduces the spurious 160-day peak in C_{20} series.



Impact of SLR on monthly $GRACE_{K\text{-}Band}$ + $GRACE_{GPS}$ solutions in terms of the RMS of the differences GRACE only – combined.



Spectra of monthly C20 -values from 2003-2013. GRACE solutions are affected by spurious signal at 160d-period that is cured by the combination with SLR.

Gravity Field and Orbit Determination

C_{20} causes an acceleration:

$$\begin{Bmatrix} R \\ S \\ W \end{Bmatrix} = \frac{3}{2}\frac{GMa_e^2\Delta C_{20}}{r^4}\begin{Bmatrix} 1-\frac{3}{2}\sin^2 i+\frac{3}{2}\sin^2 i\sin^2 u \\ \sin^2 i\sin 2u \\ \sin 2i\boxed{\sin u} \end{Bmatrix}$$

(in Radial *R*, along-track *S*, out-of-plane *W*)

Correlation between a change in C_{20} and a once-per-Rev acceleration in the out-of-plane direction *W*

Impact on orbit parameterization !

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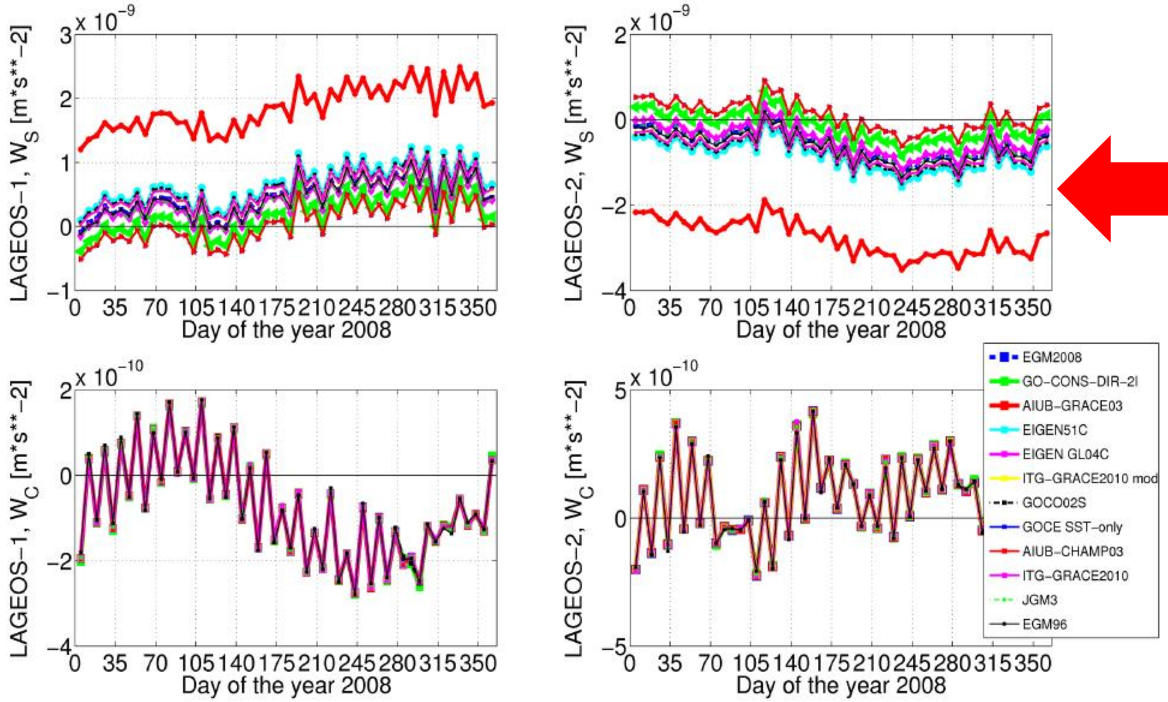
Gravity Field and Orbit Determination

C_{20} causes an acceleration:

$$\begin{Bmatrix} R \\ S \\ W \end{Bmatrix} = \frac{3}{2}\frac{GMa_e^2\Delta C_{20}}{r^4}\begin{Bmatrix} 1-\frac{3}{2}\sin^2 i+\frac{3}{2}\sin^2 i\sin^2 u \\ \sin^2 i\sin 2u \\ \sin 2i\,\boxed{\sin u} \end{Bmatrix}$$

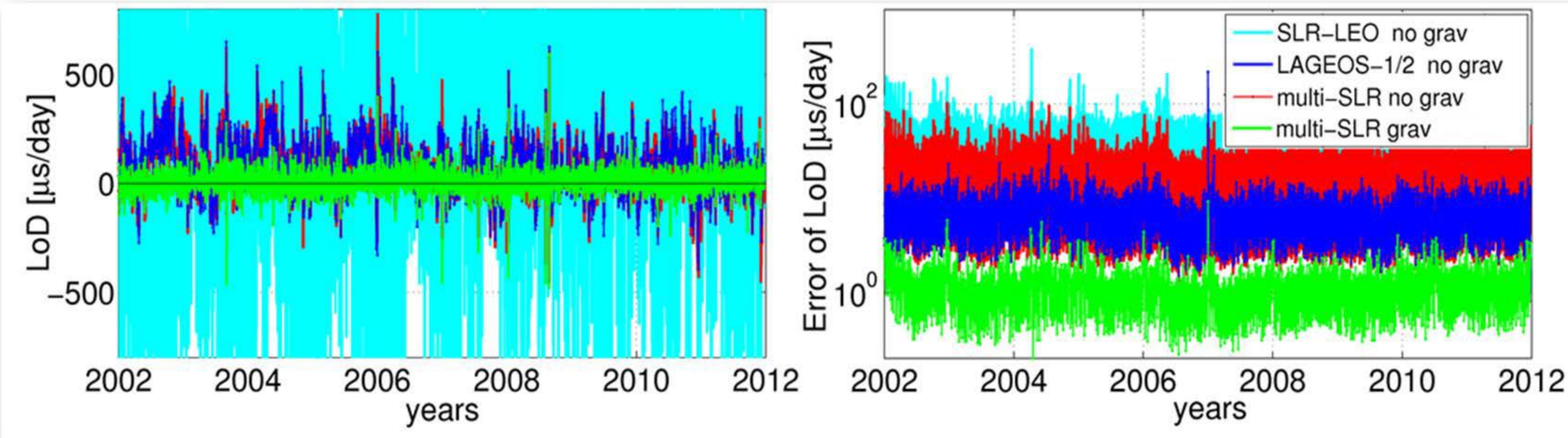
(in Radial *R*, along-track *S*, out-of-plane *W*)

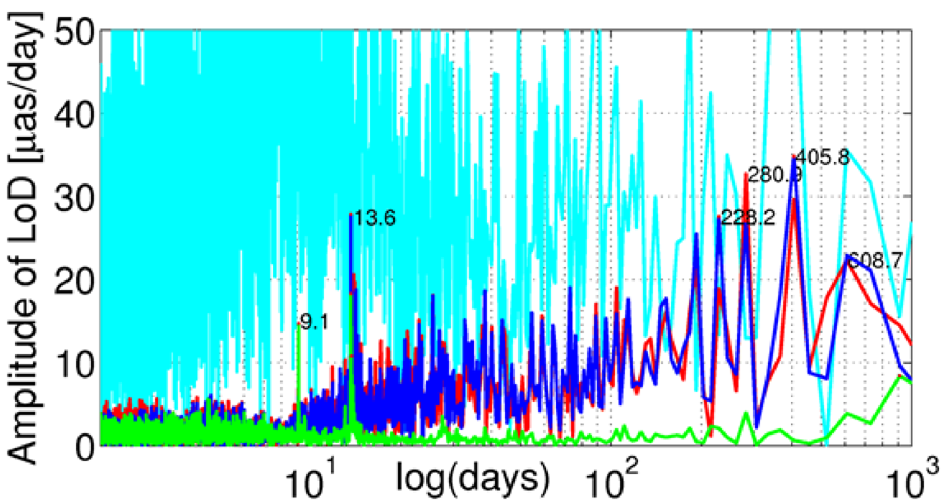


Sine component of *W* is sensitive to different C20 values of the a priori gravity field

Figure 3.2: Empirical out-of-plane W_S and W_C parameters for LAGEOS-1 (left) and LAGEOS-2 (right). Note the different scales.

Gravity Field and Earth Rotation: LOD

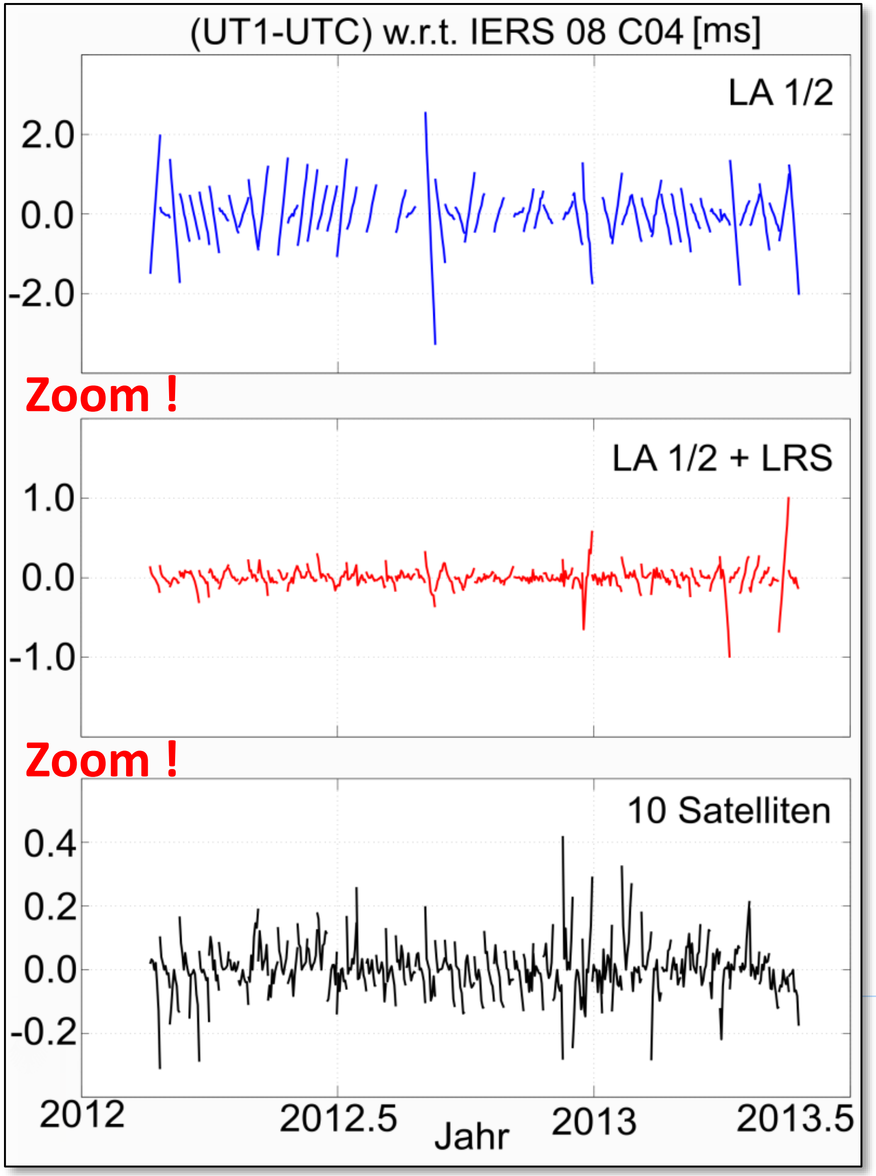




Simultaneous estimation of LOD and Gravity Field is needed to:

- Reduce the offset of LOD estimates
- Reduce the a posteriori error of LOD estimates
- Reduce artificial signals with periods corresponding to orbit modelling issues (e.g., draconitic year)

Gravity Field and Earth Rotation: LOD

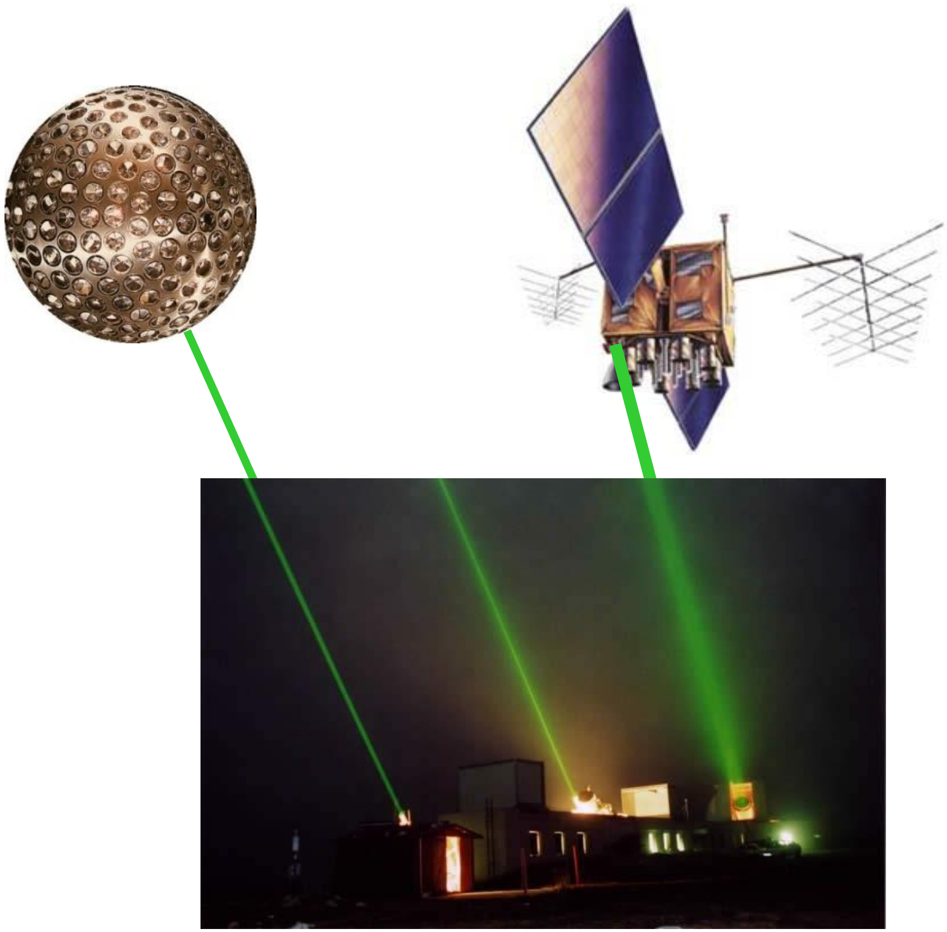


Systematic error in LOD deflects the dUT polygon

A combination with different SLR satellites reduces the systematics.

- Decrease of the systematic LOD error:
- Factor 4 due to inclusion of LARES (in addition to LAG-1/-2)
- Factor 10 due to the 10-satellite combination

Thank you for your kind attention!



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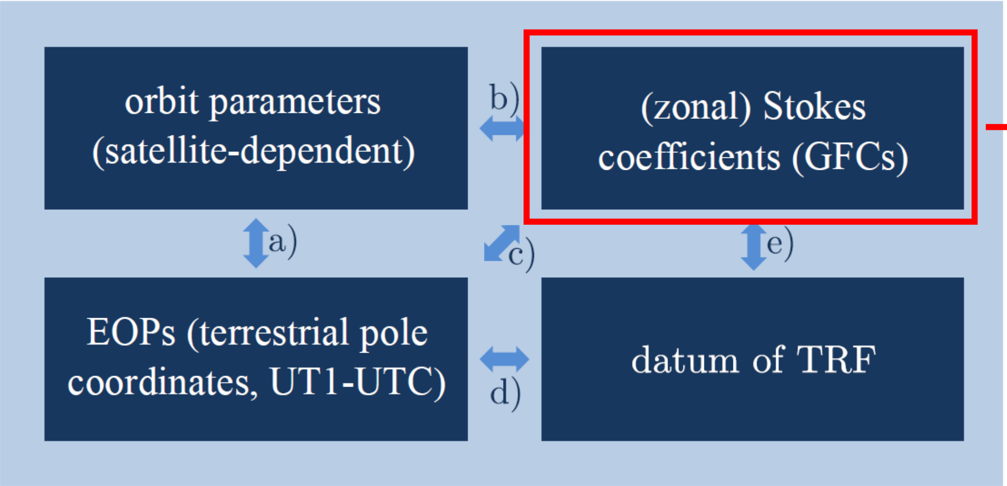
Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters

- Due to the high sensitivity of SLR observations to the fundamental geodetic parameters, correlations might falsify reliable estimates



major focus in this presentation

➢ Correlations related to Stokes coefficients

b) correlations of orbit parameters and Stokes coefficients

c) correlations of LOD and C_{l0}; x_p/y_p with C_{21}/S_{21}

e) correlation of TRF scale with C_{00}; origin with $C_{10}/C_{11}/S_{11}$; orientation with $C_{21}/S_{21}/C_{22}/S_{22}$

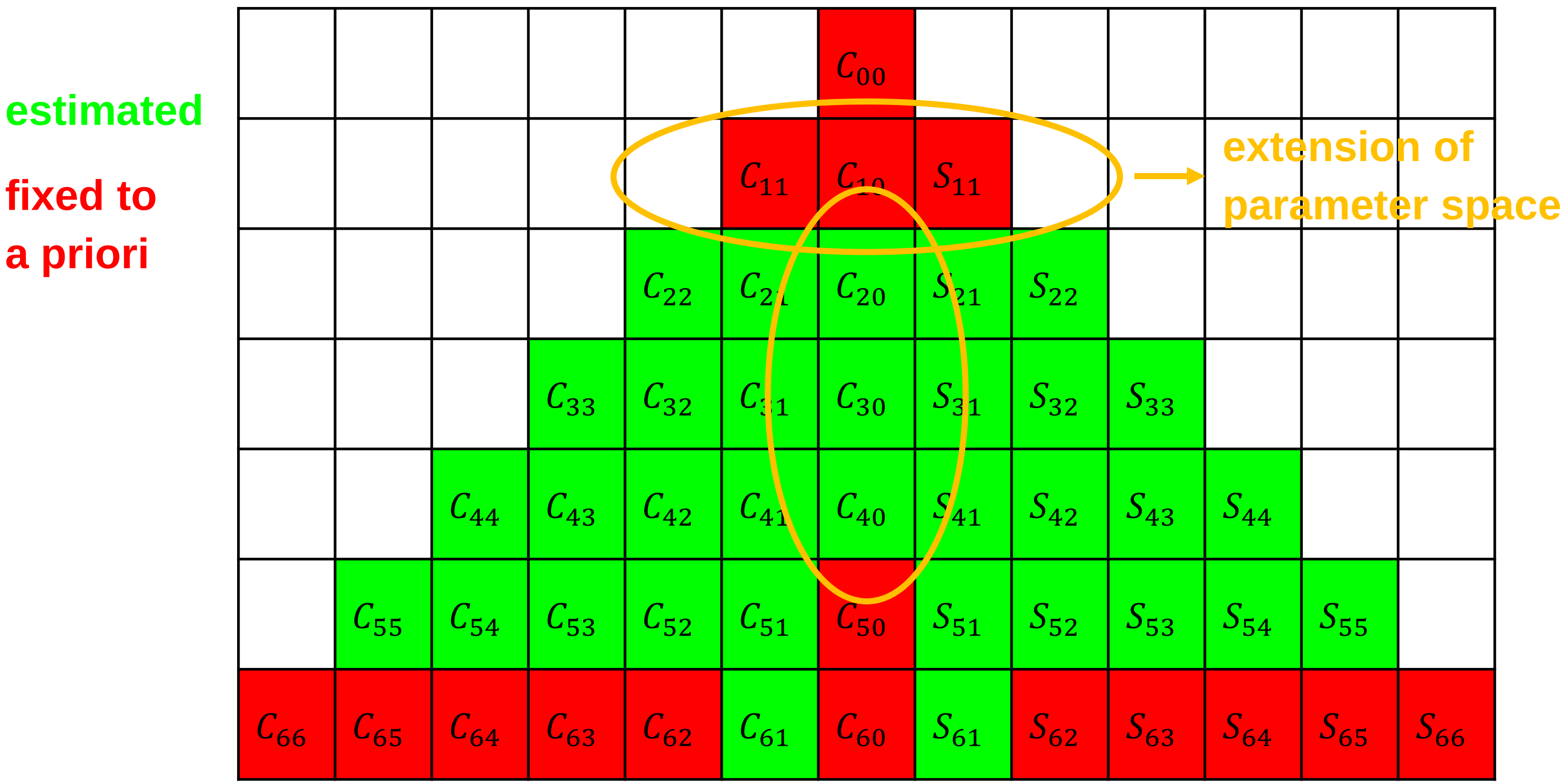
Summary

+ Improvement

– Degradation

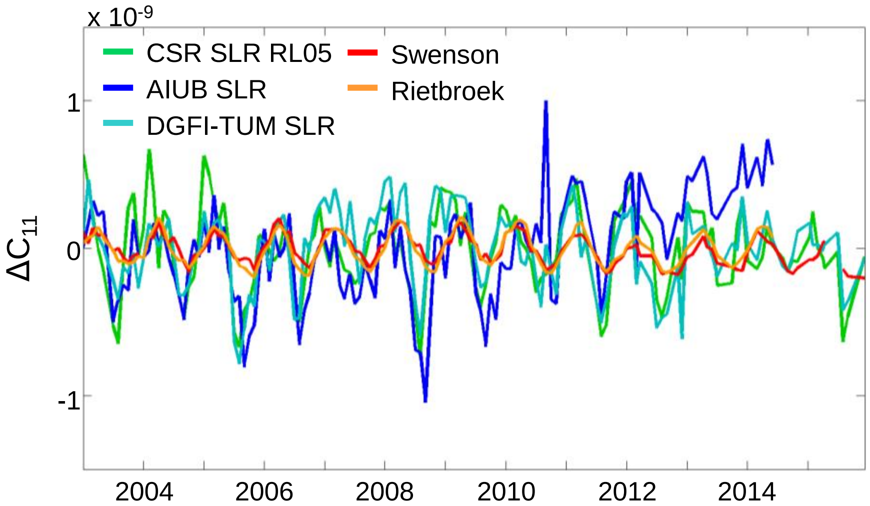
		4-sat. (ref.)	11-sat. value	11-sat. [%]	4-sat. + AJI value	4-sat. + AJI [%]	4-sat. + STA value	4-sat. + STA [%]	4-sat. + STE value	4-sat. + STE [%]	4-sat. + LTS value	4-sat. + LTS [%]	4-sat. + LRS value	4-sat. + LRS [%]
TRF [mm]	WRMS (Tx)	6.2	5.0	11.3	6.0	3.2	5.4	12.9	5.3	14.5	5.5	11.3	5.3	14.5
	wmean (Tx)	3.3	2.5	24.2	1.6	51.5	2.8	15.2	3.5	6.1	3.0	9.1	3.3	0.0
	WRMS (Ty)	6.3	6.0	4.8	6.3	0.0	5.7	9.5	5.6	11.1	5.7	9.5	5.5	12.7
	wmean (Ty)	−4.6	−2.9	37.0	−3.2	30.4	−3.3	28.3	−3.7	19.6	−4.6	0.0	−3.7	19.6
	WRMS (Tz)	9.8	6.4	34.7	7.5	23.5	9.5	3.1	8.1	17.3	9.5	3.1	9.0	8.2
	wmean (Tz)	0.5	−2.6	420.0	−3.0	500.0	−1.2	140	−0.2	60.0	−0.3	40.0	0.0	100.0
	WRMS (Sc)	6.7	5.4	19.4	7.6	13.4	5.7	14.9	6.7	0.0	6.6	1.5	5.9	11.9
	wmean (Sc)	4.7	9.3	97.9	16.0	240.4	5.0	6.4	4.5	4.3	5.2	10.6	4.3	8.5
	WRMS (north)	11.9	9.3	21.8	11.3	5.0	10.5	11.8	10.8	9.2	11.1	6.7	11.1	6.7
	WRMS (east)	10.8	8.7	19.4	10.0	7.4	10.1	6.5	9.9	8.3	10.6	1.9	10.6	1.9
	WRMS (height)	12.7	11.8	7.1	12.1	4.7	12.5	1.6	12.6	0.8	12.3	3.1	12.6	0.8
EOP [mas, ms/d]	WRMS (x-pole)	0.385	0.320	16.9	0.360	6.5	0.356	7.5	0.366	4.9	0.361	6.2	0.414	7.5
	wmean (x-pole)	−0.107	0.004	96.3	−0.053	50.5	−0.052	51.4	−0.079	26.2	−0.069	35.5	−0.102	4.7
	WRMS (y-pole)	0.387	0.305	21.2	0.355	8.3	0.352	9.0	0.353	8.8	0.355	8.3	0.384	0.8
	wmean (y-pole)	0.165	0.027	83.6	0.035	78.8	0.099	40.0	0.118	28.5	0.134	18.8	0.193	17.0
	WRMS (ΔLOD)	0.047	0.043	8.5	0.040	14.9	0.039	17.0	0.036	23.4	0.035	25.5	0.038	19.1
	wmean (ΔLOD)	−0.001	0.003	200.0	−0.006	500.0	0.009	800	0.002	100.0	0.004	300.0	0.001	0.0
GFC $\cdot 1^{-10}$ [-]	WRMS ($C_{(2,0)}$)	2.0172	1.0554	47.7	1.1151	44.7	1.2835	36.4	1.1945	40.8	1.2655	37.3	1.1813	41.4
	WRMS ($C_{(3,0)}$)	17.224	1.2346	92.8	0.9831	94.3	14.726	14.5	8.4124	51.2	10.414	39.5	7.7003	55.3
	WRMS ($C_{(4,0)}$)	6.9305	0.8861	87.2	3.8998	43.7	4.0417	41.7	1.0756	84.5	1.7648	74.5	1.3144	81.0
	WRMS* ($C_{(n,m)}$)			79.3		64.4		66.1		52.3		41.9		61.7

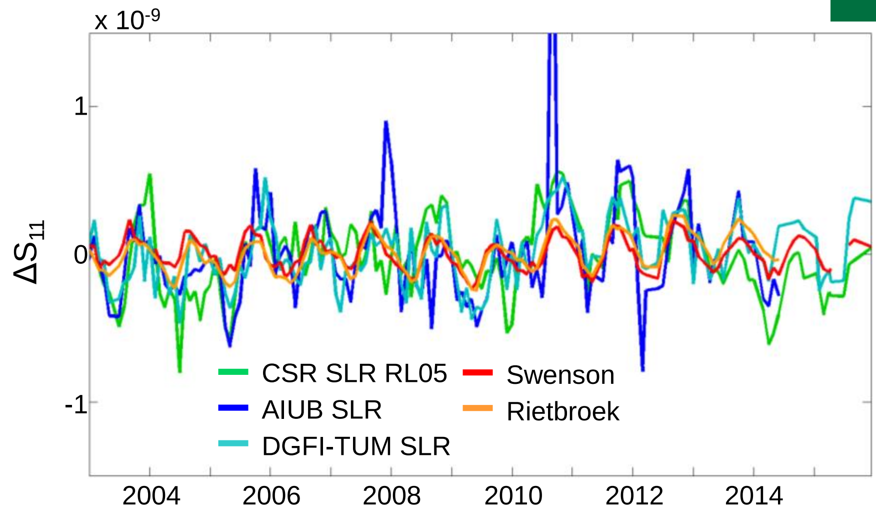
Estimation of reliable low degree spherical harmonics

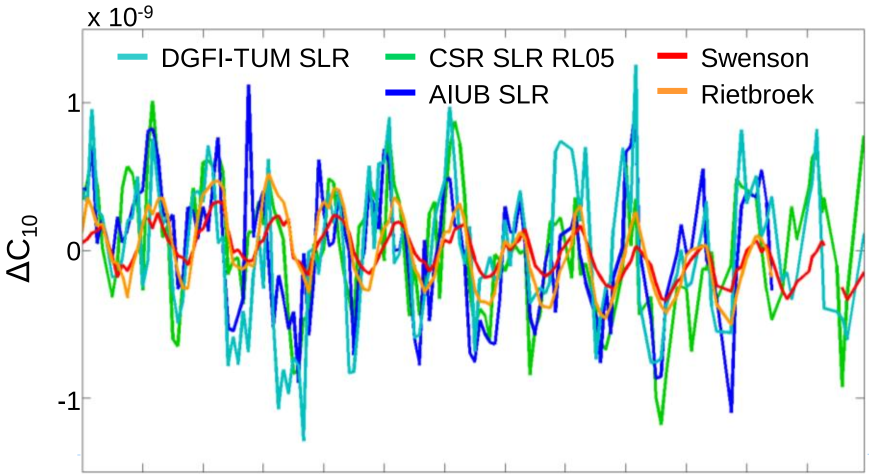


Solution setup as used by CSR/GSFC: Estimation of a reliable subset of coefficients

Scatter of the centered degree-1 Stokes coefficient solutions







- CSR SLR RL05: 5-satellite solution (Cheng et al., 2013)
- AIUB SLR: 8-satellite solution (Sosnica et al., 2015)
- DGFI-TUM SLR: 11-satellite solution, TRF and EOP fixed (Bloßfeld et al., submitted)
- Swenson (2008): GRACE, geophysical model for ocean bottom pressure (OBP)
- Rietbroek (2016): GRACE, OBP, GPS

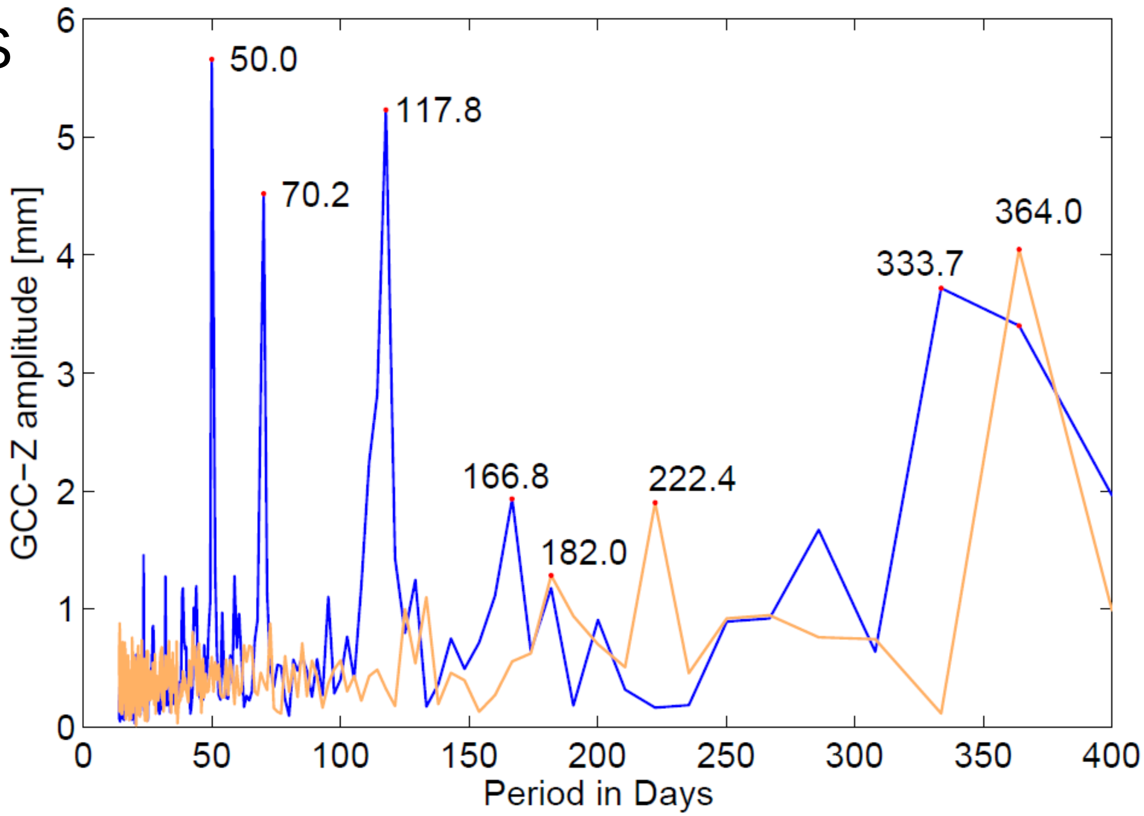
Geocenter: Single techniques

Draconitic year is visible: GNSS = 352d, LAG-2 = 222d

+ Harmonics for GNSS

GNSS-only

SLR-only



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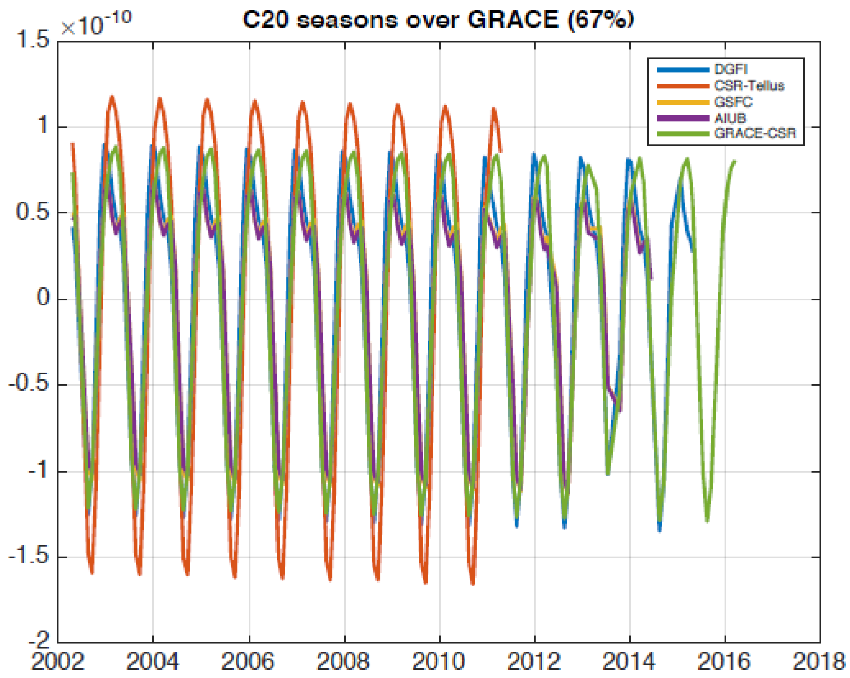
Validation of low degree spherical harmonics (M. Talpe)

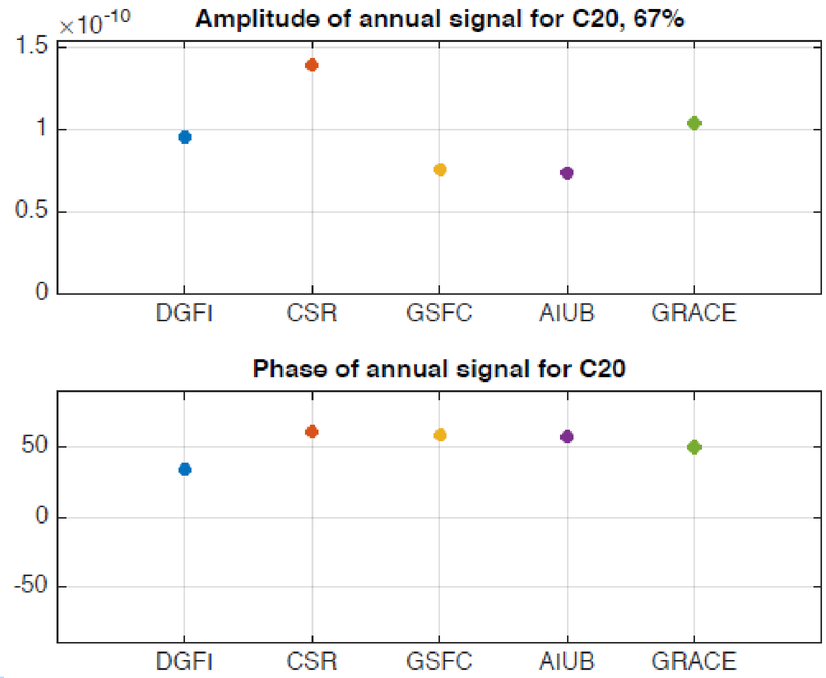
How can we validate the SLR-only low degree spherical harmonics?

- Compare seasonal signals of individual coefficients
- Compare trend signals of individual coefficients
- Map-based comparison with GRACE since individual coefficients are correlated
- Investigation of mass change in Greenland and Antarctica by comparison with GRACE
- Compare annual/semi-annual signals of maps (not shown here)
- Compare degree variances of solutions (Bloßfeld et al., 2015)
- Compare EOF modes to capture the main signal content (not shown here)
- Investigate spatial coherence (not shown here)

Validation of low degree spherical harmonics

- How can we validate the SLR-only low degree spherical harmonics?
  - ➢ Compare seasonal signals of individual coefficients (M. Talpe)





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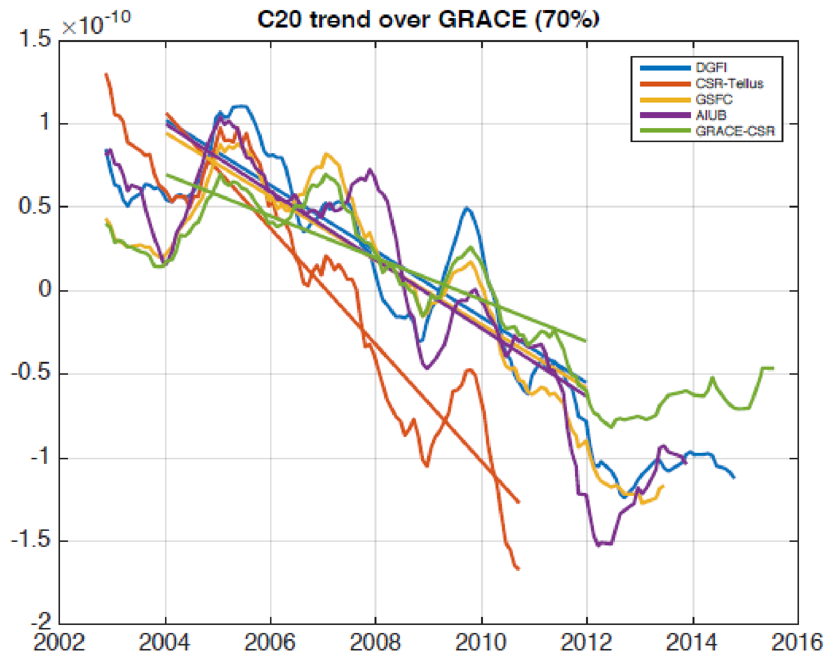
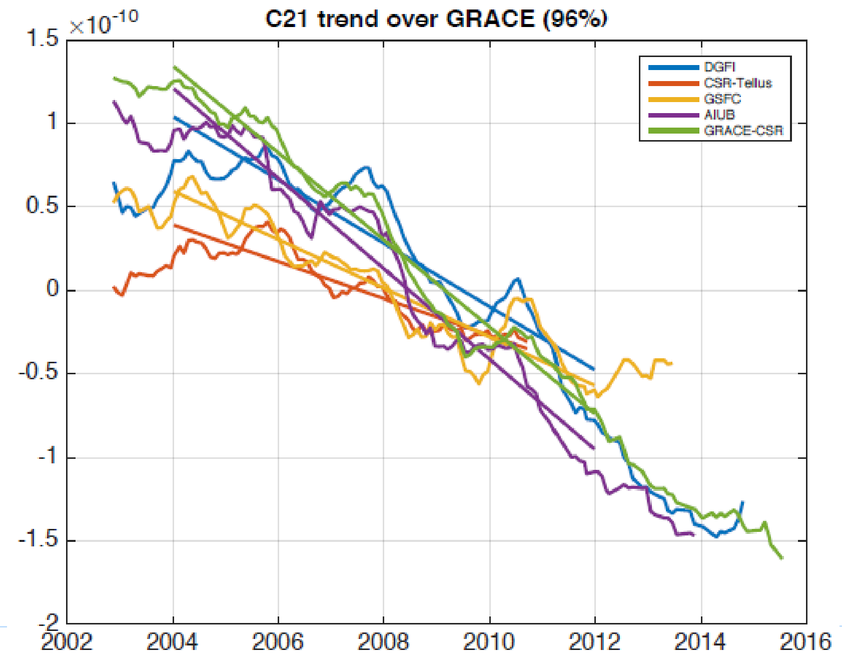
Validation of low degree spherical harmonics

- How can we validate the SLR-only low degree spherical harmonics?
  - ➢ Compare trend signals of individual coefficients (M. Talpe)





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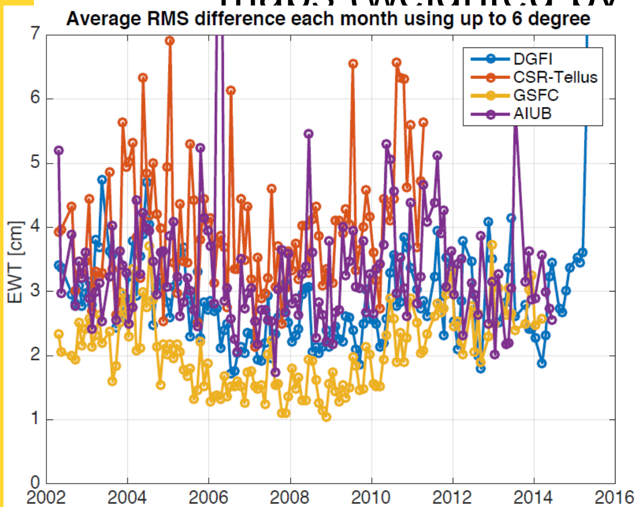
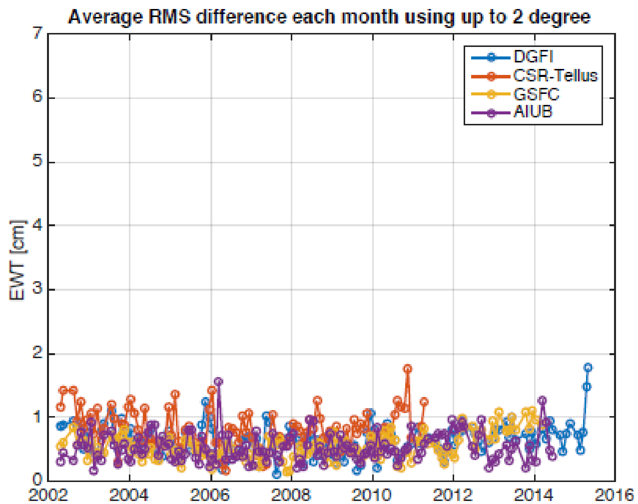
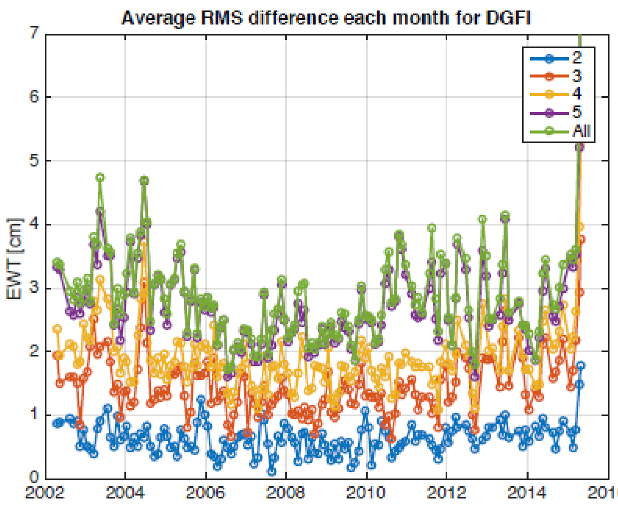
Validation of low degree spherical harmonics

- How can we validate the SLR-only low degree spherical harmonics?
  - ➢ Map-based comparison with GRACE since individual coefficients are correlated (M. Talpe)
  - All solutions are expanded in Equivalent Water Thickness maps and compared to their GRACE equivalent. The RMS of the difference of the two maps (weighted by latitude) is calculated. High RMS means large difference







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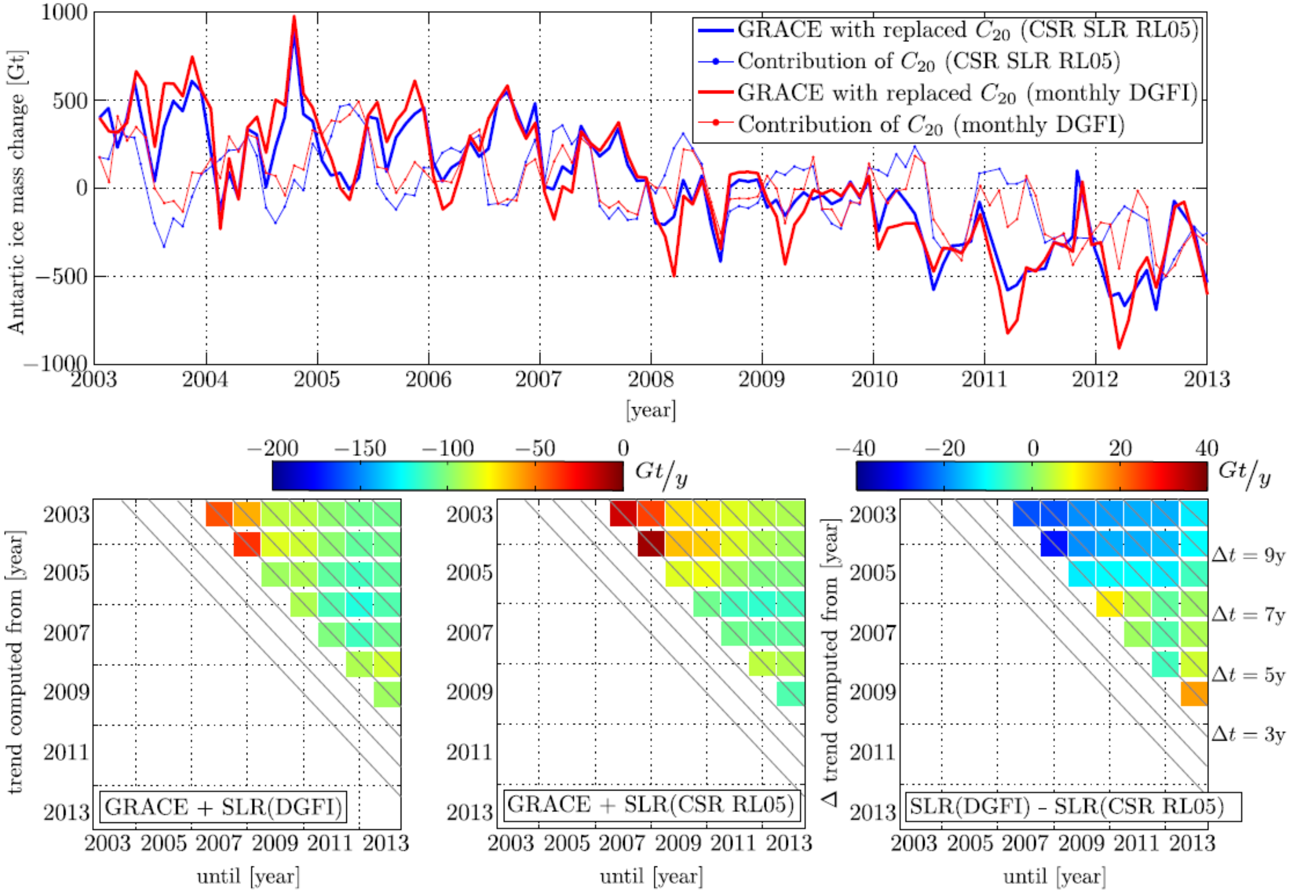
Validation of low degree spherical harmonics

- How can we validate the SLR-only low degree spherical harmonics?
  - ➢ Investigation of mass change in Greenland and Antarctica by comparison with GRACE

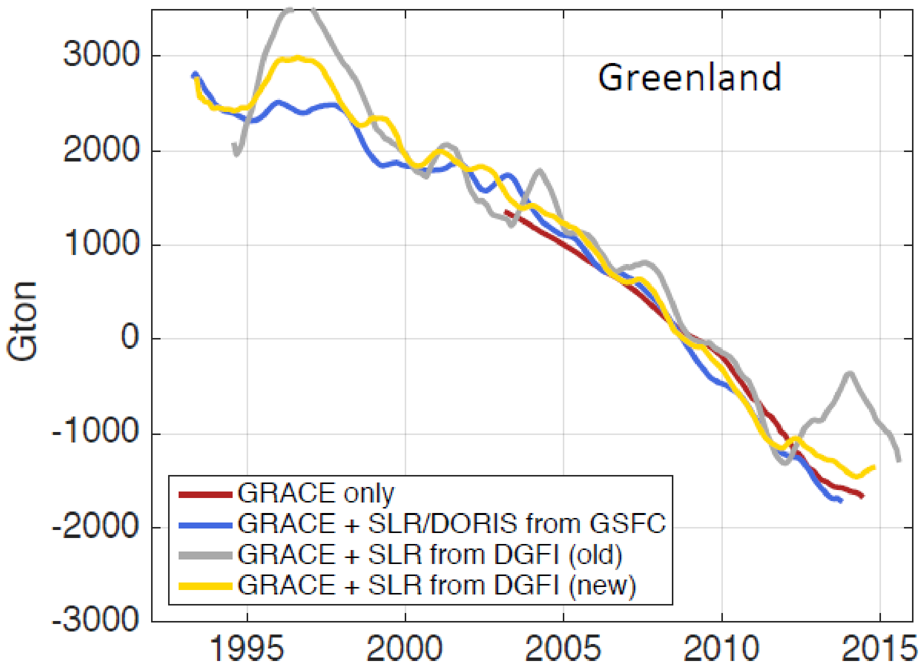


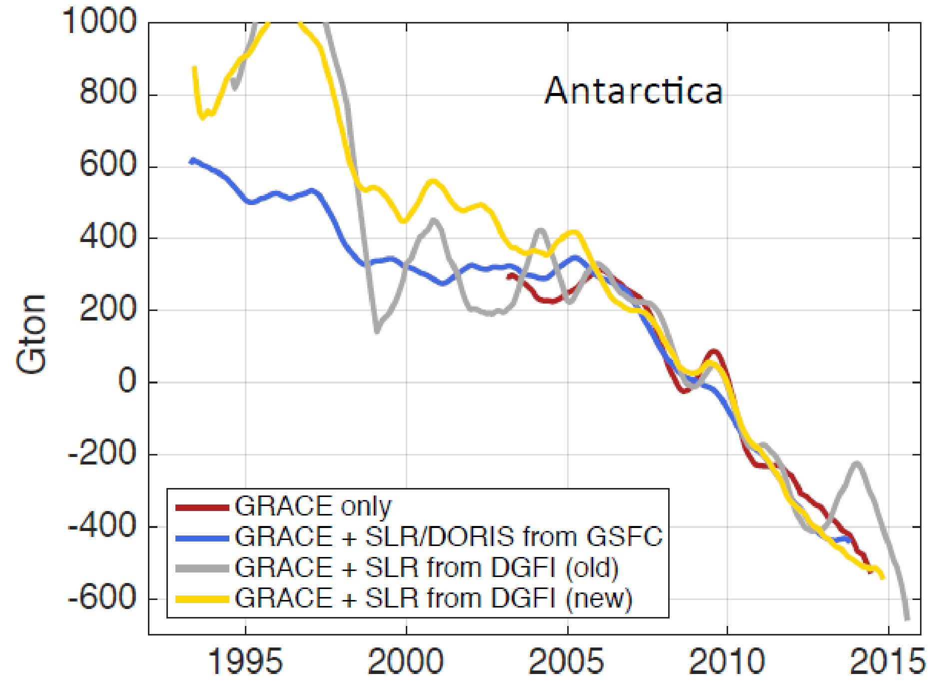
Bloßfeld M., Müller H., Gerstl M., Stefka V., Bouman J., Göttl F., Horwath M.: **Second-degree Stokes coefficients from multi-satellite SLR**. Journal of Geodesy 89(9): 857-871, 10.1007/s00190-015-0819-z, 2015

Validation of low degree spherical harmonics

- How can we validate the SLR-only low degree spherical harmonics?

  ➢ Investigation of mass change in Greenland and Antarctica by comparison with GRACE (M. Talpe)





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