Time varying gravity from SLR and combined SLR and high-low satellite-to-satellite tracking data

K. Sośnica (1), A. Jäggi (1), M. Weigelt (2), U. Meyer (1),
T. van Dam (2), N. Zehentner (3), T. Mayer-Gürr (3)

(1) Astronomical Institute, University of Bern, Switzerland

(2) Faculté des Sciences, de la Technologie et de la Communication, University of Luxembourg, Luxembourg

(3) Institute of Theoretical Geodesy and Satellite Geodesy, Graz University of Technology, Austria

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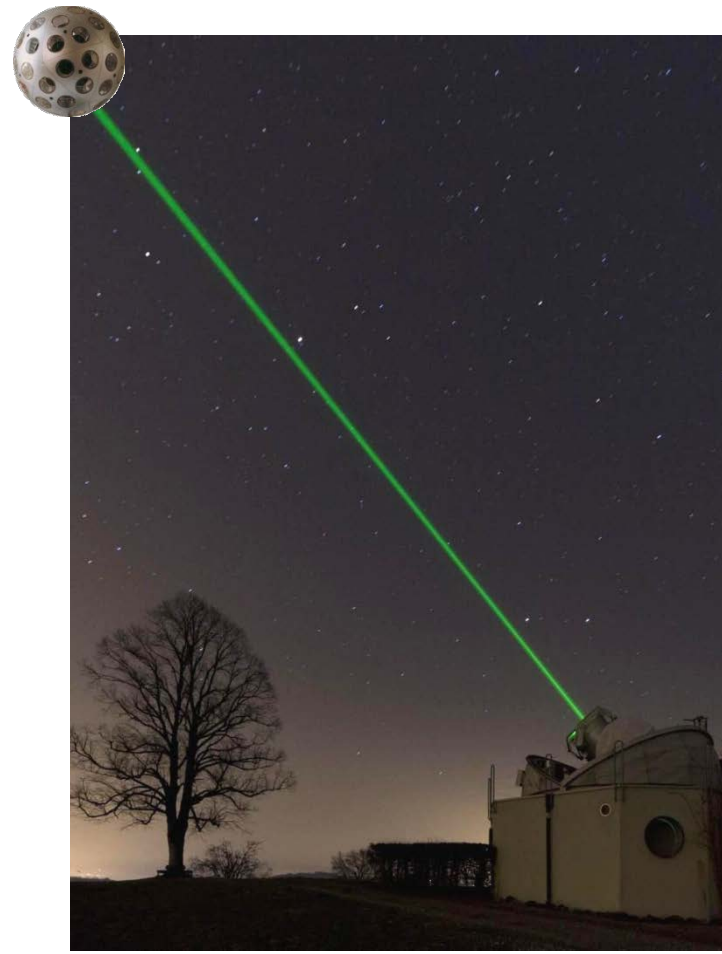
Satellite Laser Ranging (SLR)

- SLR provides very precise (at a few mm-level) distance measurements between ground stations and satellites.
- SLR geodetic satellites have minimized area-to-mass ratios. They orbit the Earth at higher altitudes than the satellite missions dedicated to gravity recovery.
- Up to now SLR observations were mostly used for deriving low-degree gravity field coefficients (mainly degree 2) or zonal harmonics.
- We show that also tesseral and sectorial harmonics up to d/o 10/10 of monthly gravity field models can be very well derived from SLR observations.

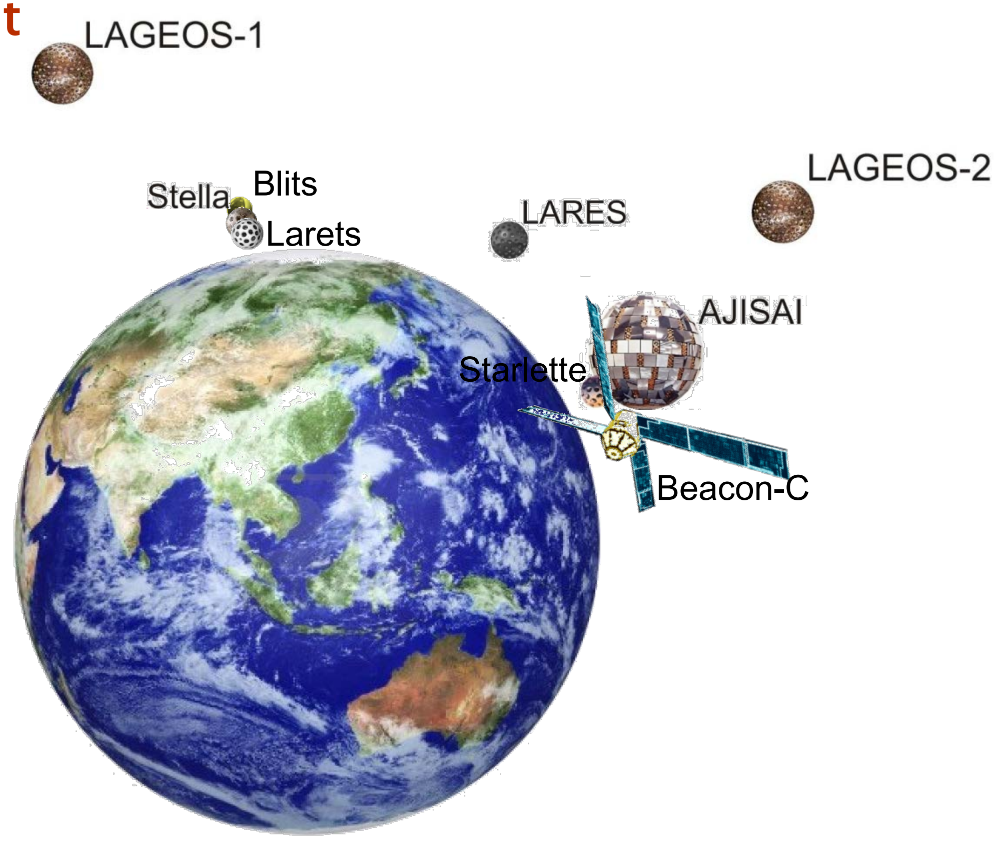


SLR station in Zimmerwald, Switzerland

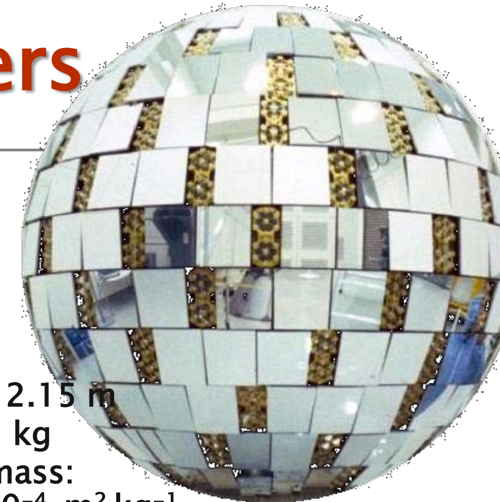
SLR-only solutions

Space Segment of SLR satellites

- Up to 9 SLR satellites with different altitudes and different inclinations are used.
- For LAGEOS-1/2 10-day arcs are generated without estimating once-per-revolution empirical accelerations in out-of-plane (due to correlations with C_{20}).
- For low orbiting satellites 1-day arcs are generated.
- Different weighting of observations is applied: from 8mm for LAGEOS-1/2 to 50mm for Beacon-C.



List of estimated parameters



Estimated parameters		SLR solutions: LAGEOS-1/2, Starlette, Stella, AJISAI, LARES, Blits, Larets, Beacon-C
Orbits	Osculating elements	$a, e, i, \Omega, \omega, u_0$ (LAGEOS: 1 set per 10 days, LEO: 1 set per 1 day)
Orbits	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)
Orbits	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)

AJISAI :

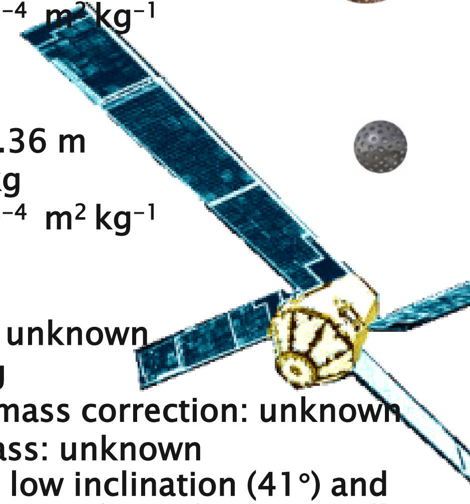
- Diameter: 2.15 m
- Mass: 685 kg
- Area-to-mass: A/m: $58 \cdot 10^{-4}$ $m^2\,kg^{-1}$

LAGEOS :

- Diameter: 0.60 m
- Mass: 407 kg
- A/m: $6.9 \cdot 10^{-4}$ $m^2\,kg^{-1}$

LARES :

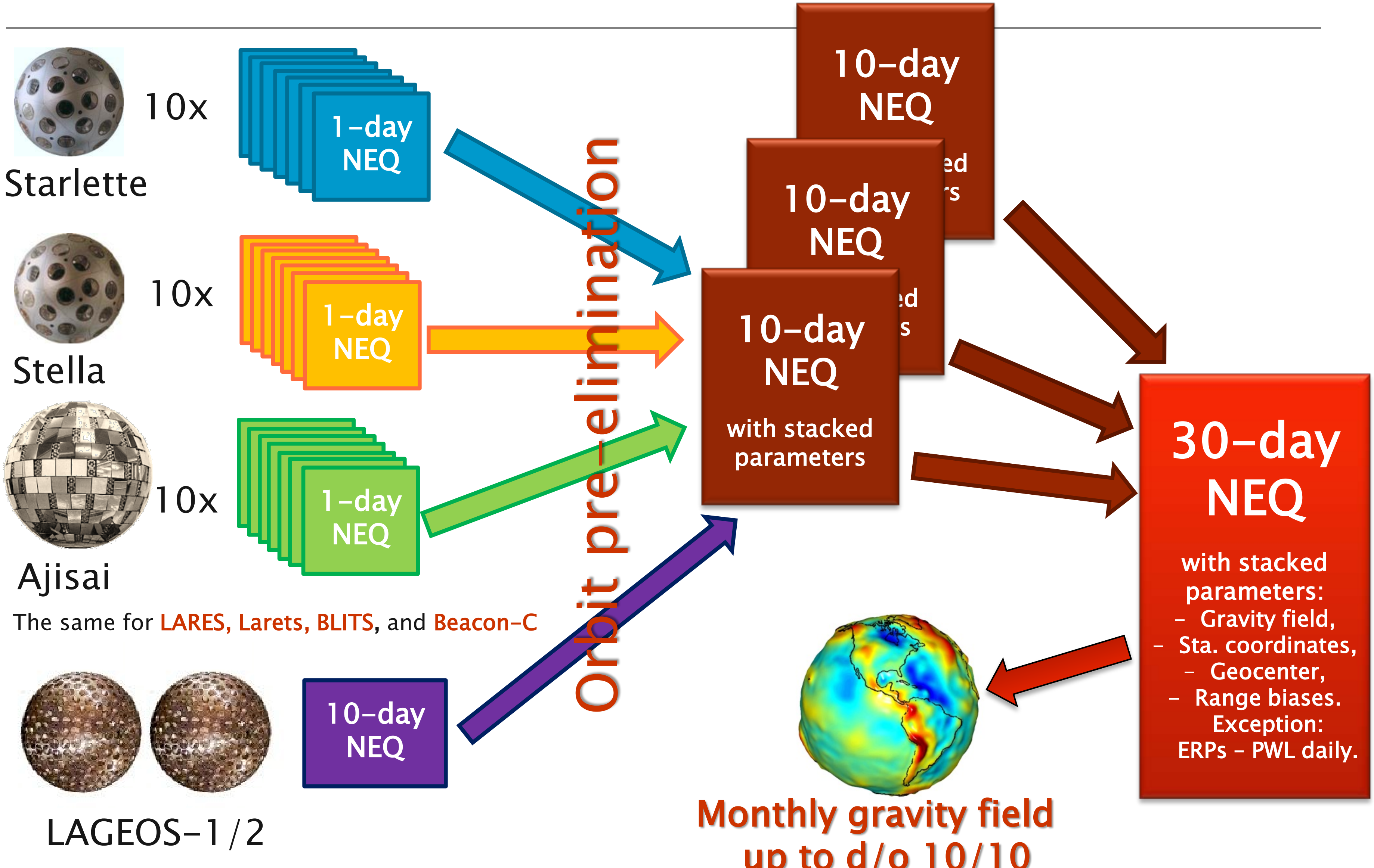
- Diameter: 0.36 m
- Mass: 387 kg
- A/m: $2.7 \cdot 10^{-4}$ $m^2\,kg^{-1}$



Beacon-C:

- Dimension: unknown
- Mass: 32 kg
- Center-of-mass correction: unknown
- Area-to-mass: unknown
  BUT: due to low inclination (41°) and large eccentricity (0.023) , this satellite can be used for decorrelation of some gravity field parameters.

Processing scheme



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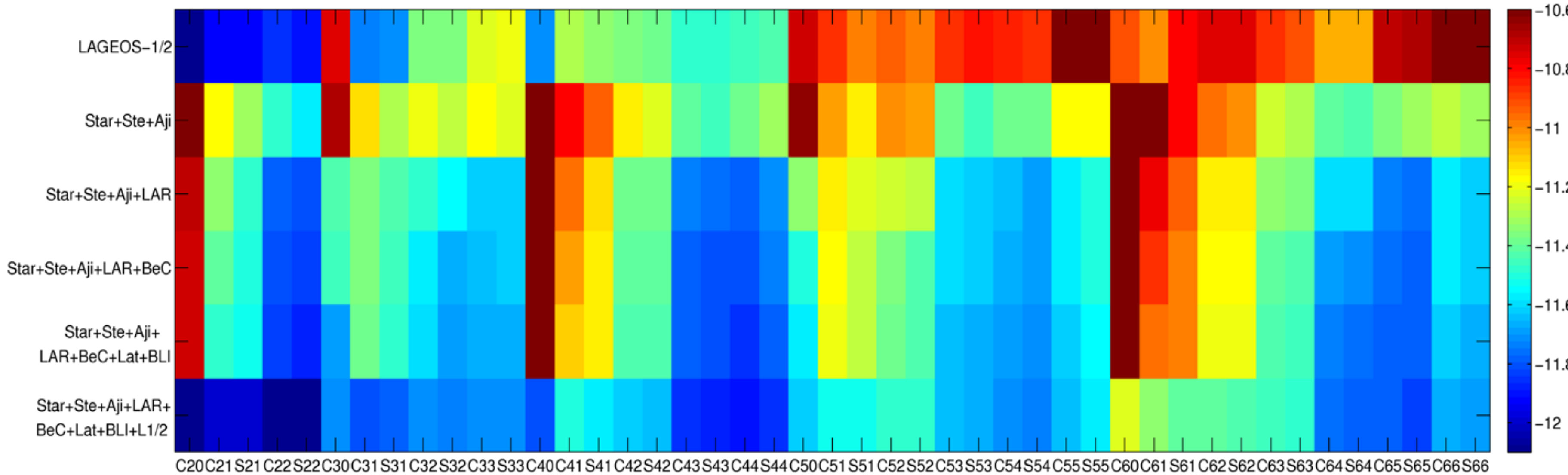
Sensitivity of SLR satellites to SH coefficients



Formal errors of coefficients up to d/o 6/6 in log scale

- LAGEOS-1/2 are very sensitive to degree 2 SH.
- LAGEOS sensitivity drops down for degrees higher than 4.
- LEOs are not very sensitive to even zonal coefficients (C20, C40, C60) due to short arcs (1-day) and estimated empirical orbit parameters.
- LARES remarkably contributes to degree 4 and 6.
- Contribution from Larets and Blits is small.

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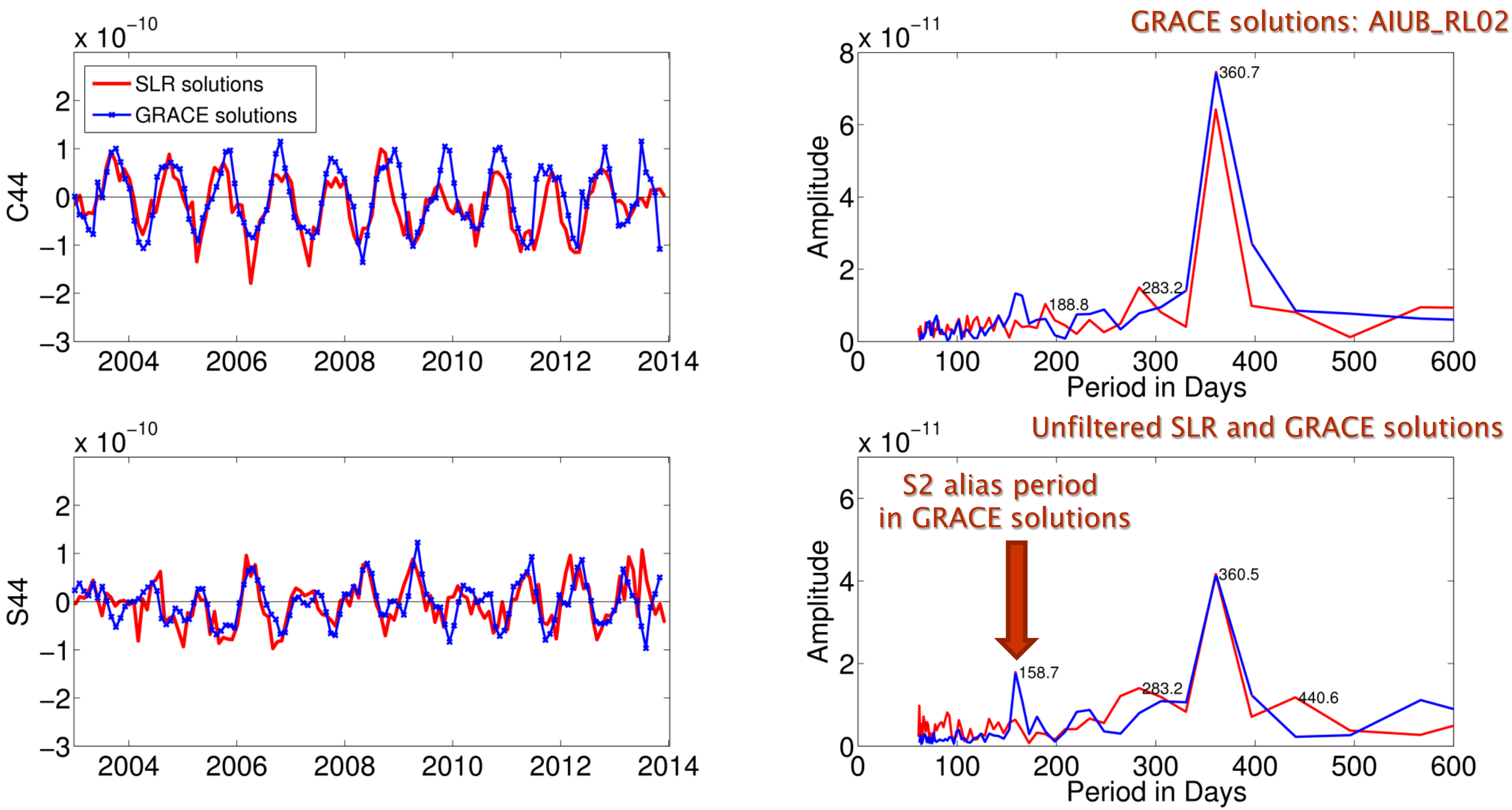
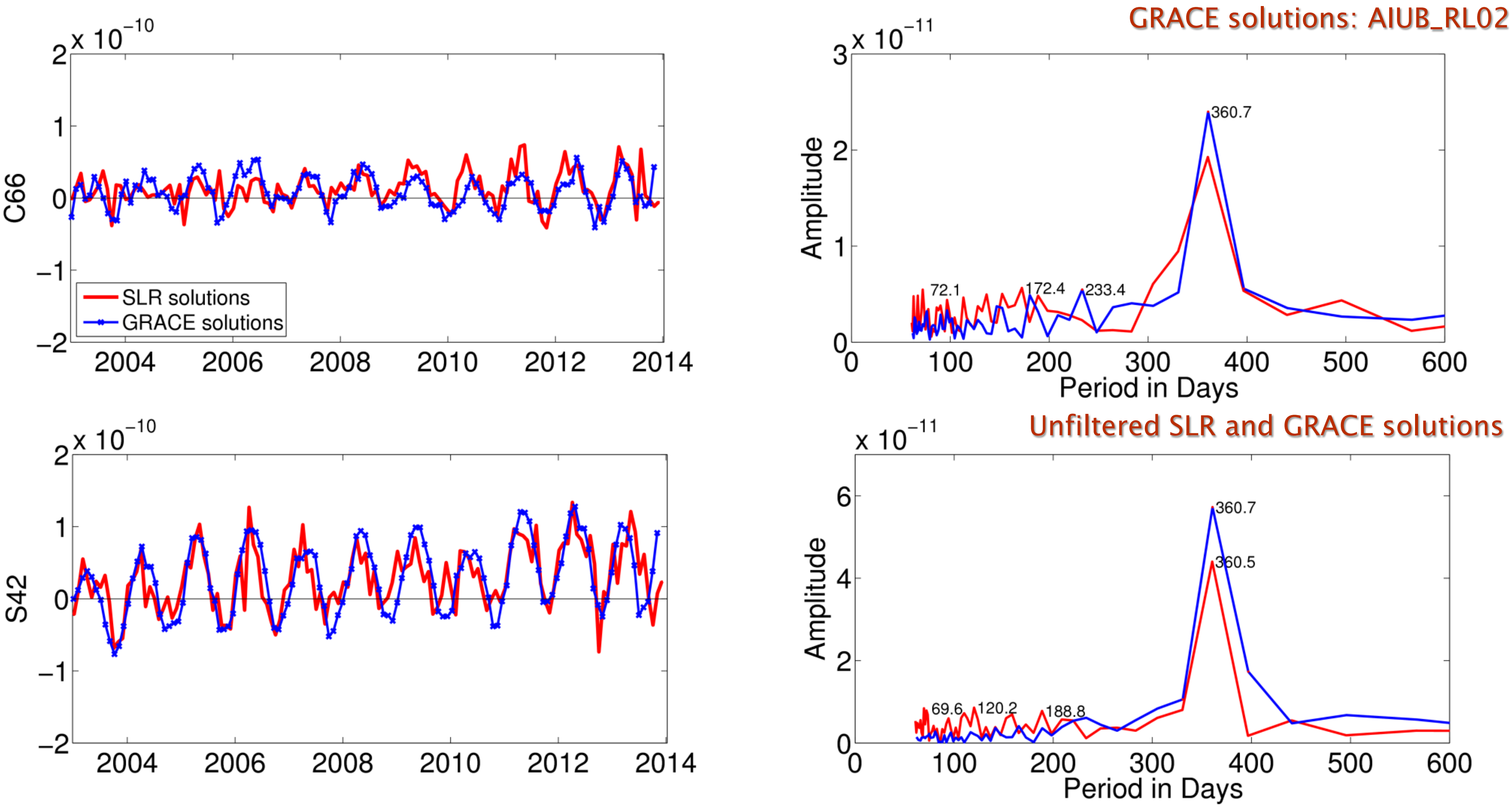
Comparison w.r.t. GRACE K-Band



SLR and GRACE solutions agree very well, especially for sectorial and tesseral SH coefficients.

Comparison w.r.t. GRACE K-Band



Even the coefficients of degree 6 can be still very well recovered by SLR.

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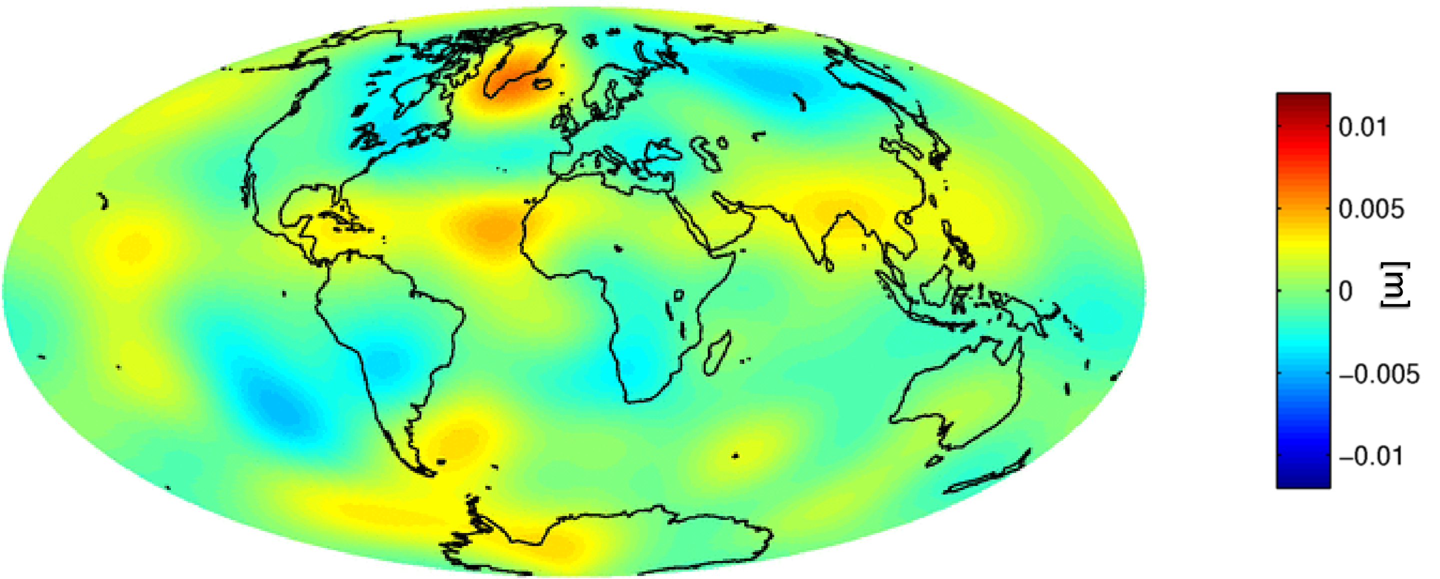
SLR-only solutions

SLR can recover the largest gravity variations, e.g., in Amazon basin, Greenland, Africa, and South-East Asia. The spatial resolution is, however, limited due to high satellite latitudes and a low number of data.



Mean monthly gravity field variations up to d/o 10/10 derived from SLR-only (no filtering applied, scale in m)

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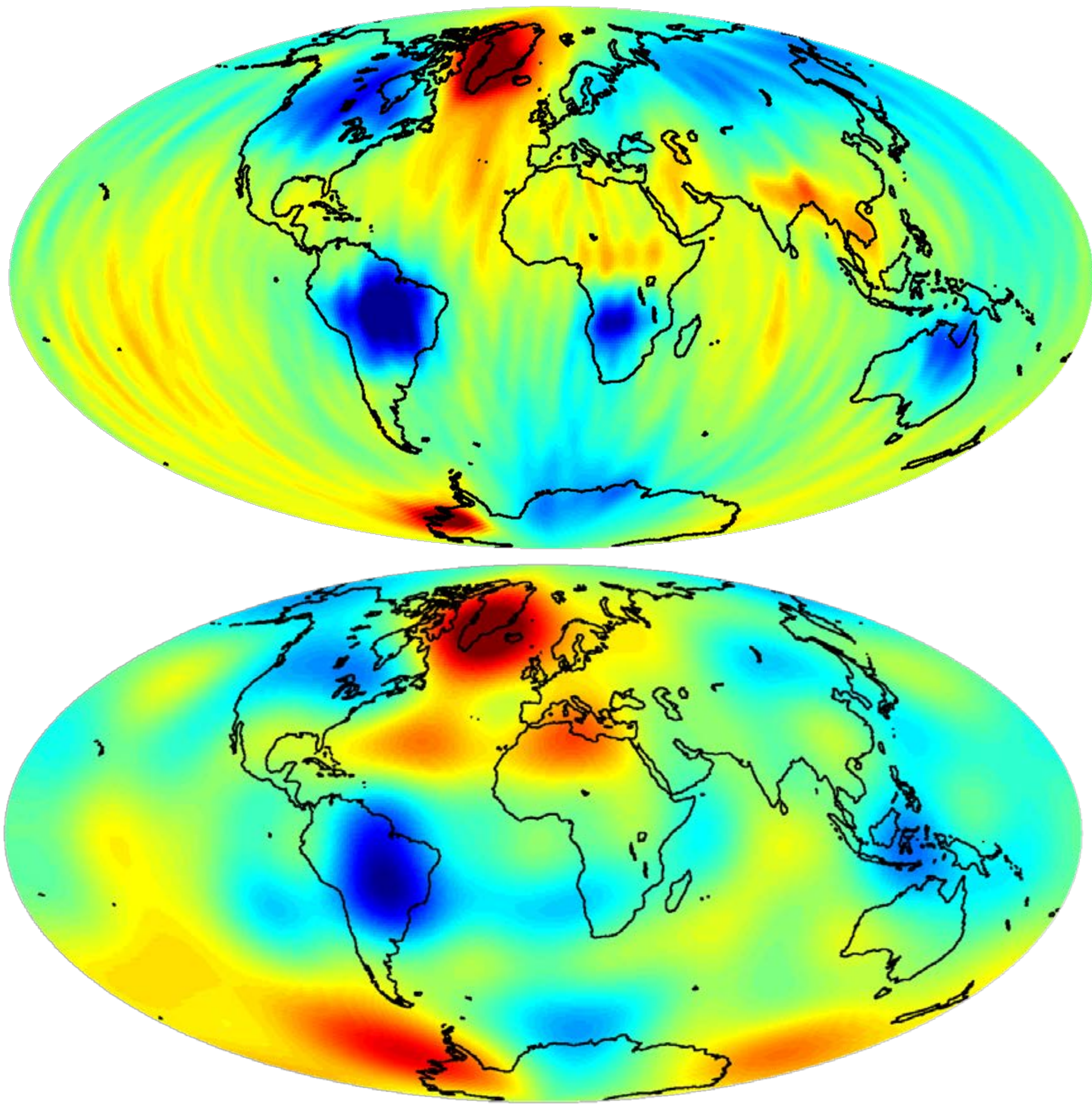
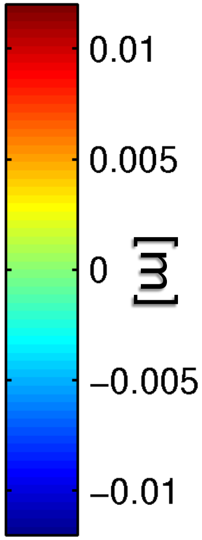
SLR-only solutions



GRACE K-band solution
AIUB-RL02,
March 2011,
up to d/o 60/60
filtering 300 km

SLR-only solution,
March 2011,
up to d/o 10/10
no filtering



SLR-only solutions

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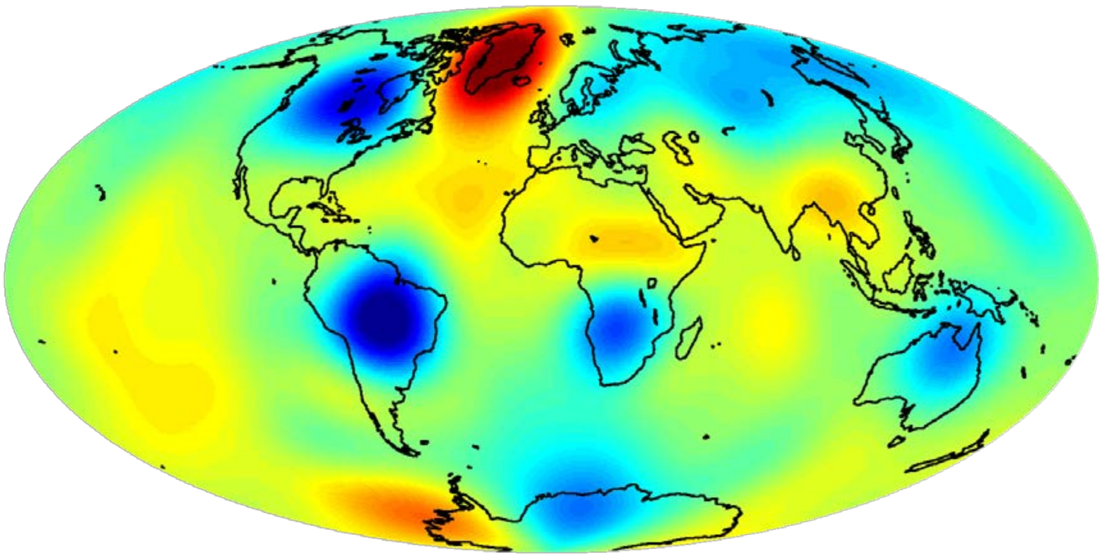

GRACE K-band solution
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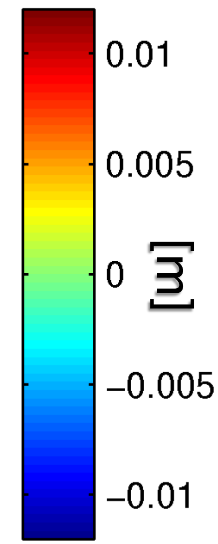
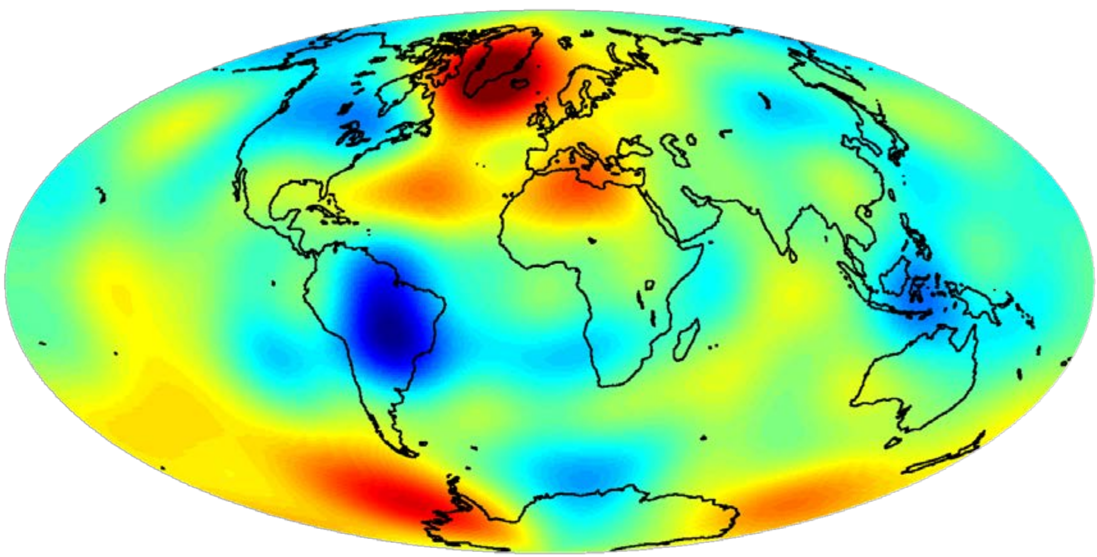
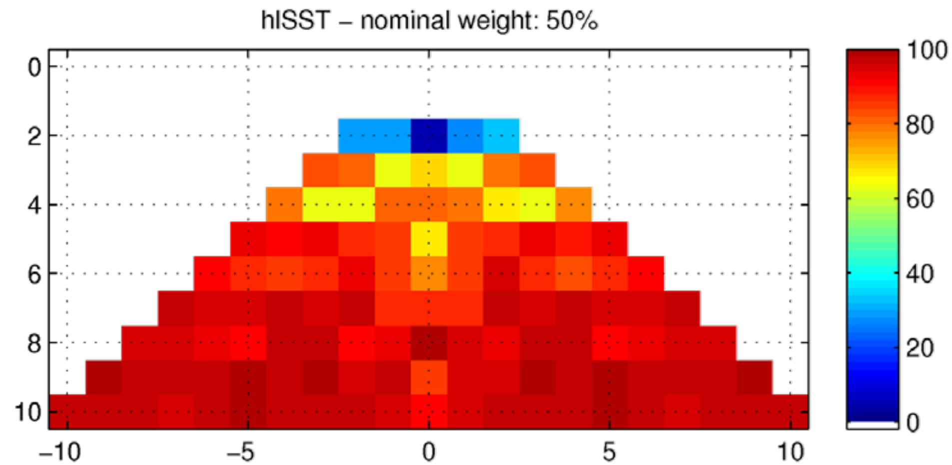


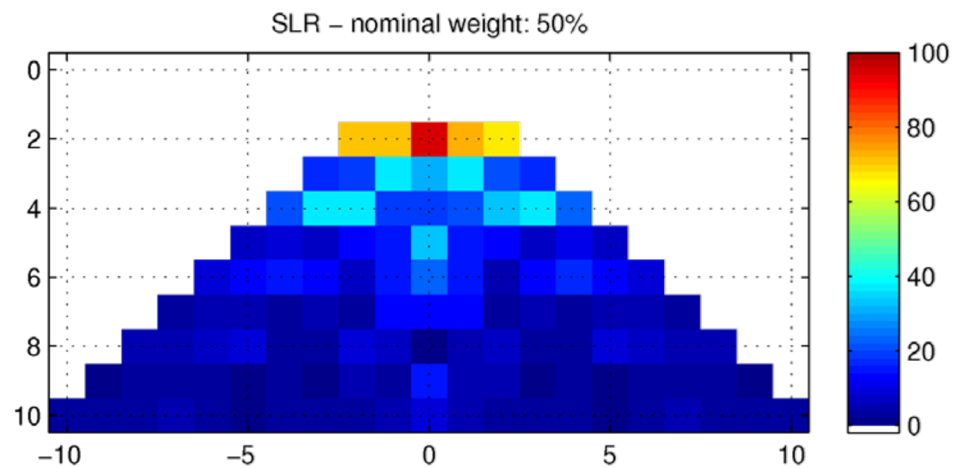


SLR-only solution,
March 2011,
up to d/o 10/10
no filtering

Combined SLR + hl-SST solutions

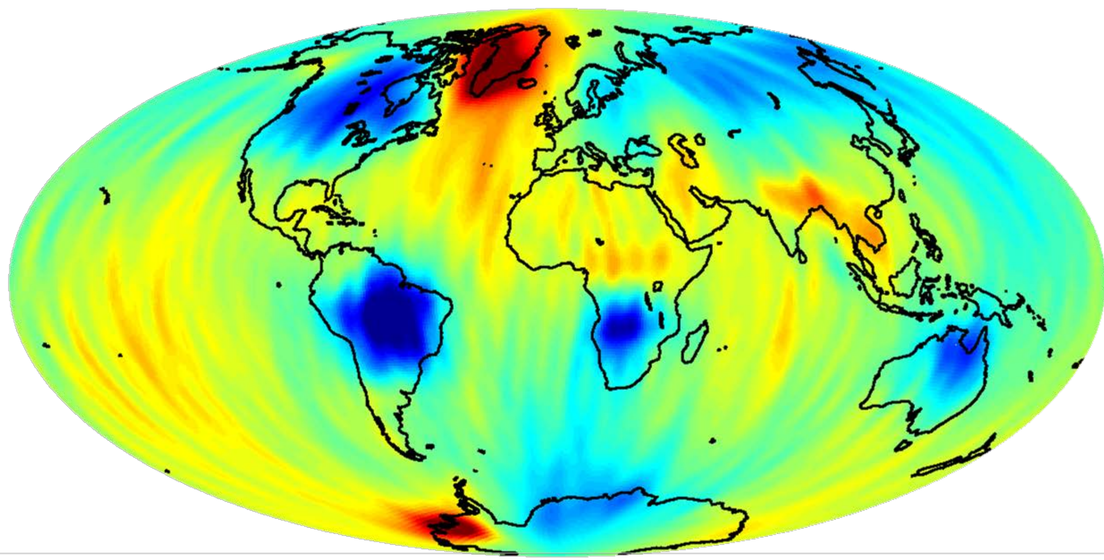
Combination of hlSST and SLR



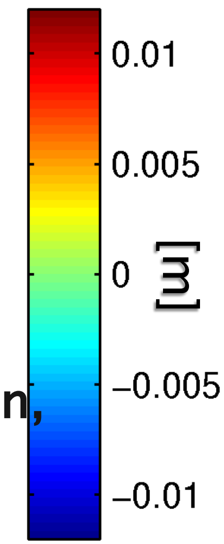


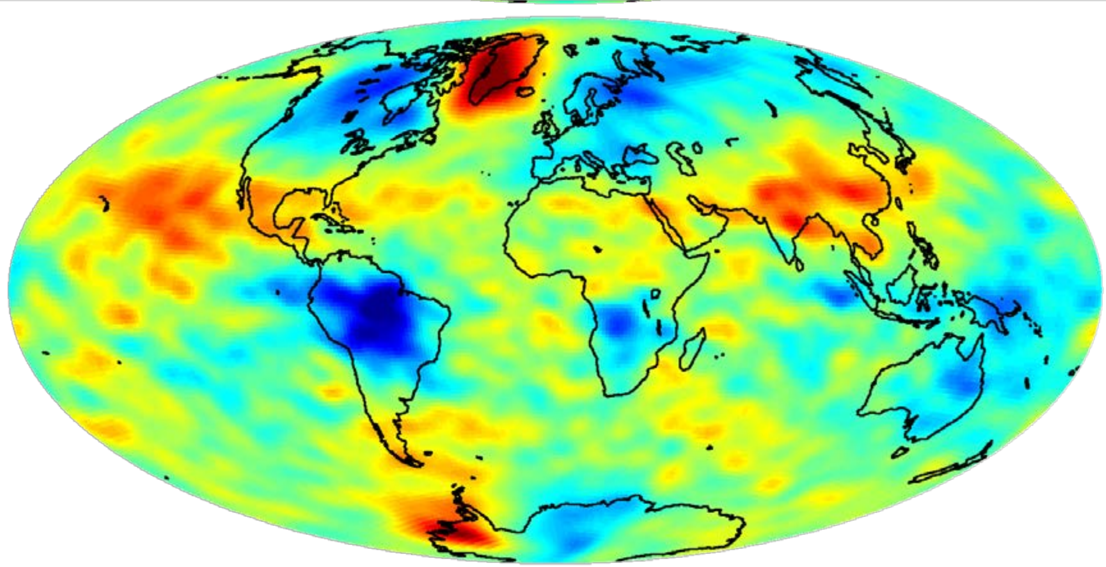
In the combination with hlSST, SLR contributes mostly to degree 2 coefficients, but the relative weighting is still an open issue.

SLR+hl-SST solutions



GRACE K-band solution,
March 2011,
up to d/o 60/60
filtering 300 km





SLR+hl-SST solution,
March 2011,
up to d/o 90/90
filtering 500 km

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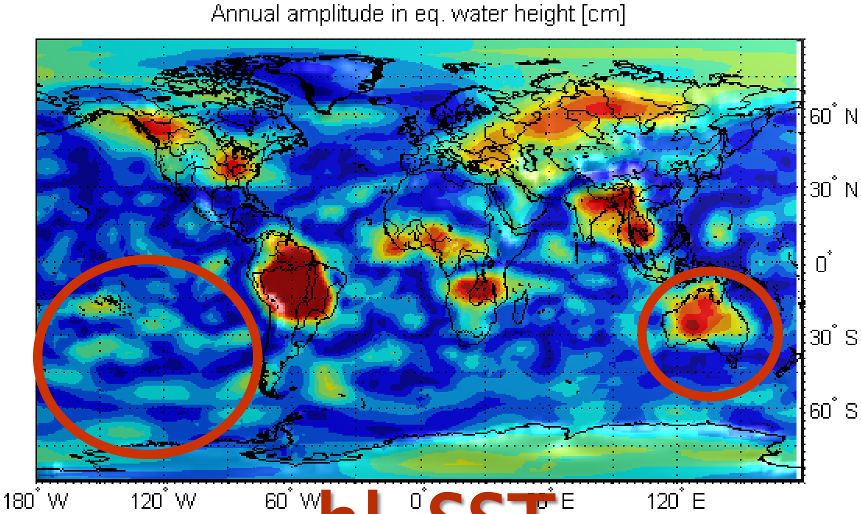
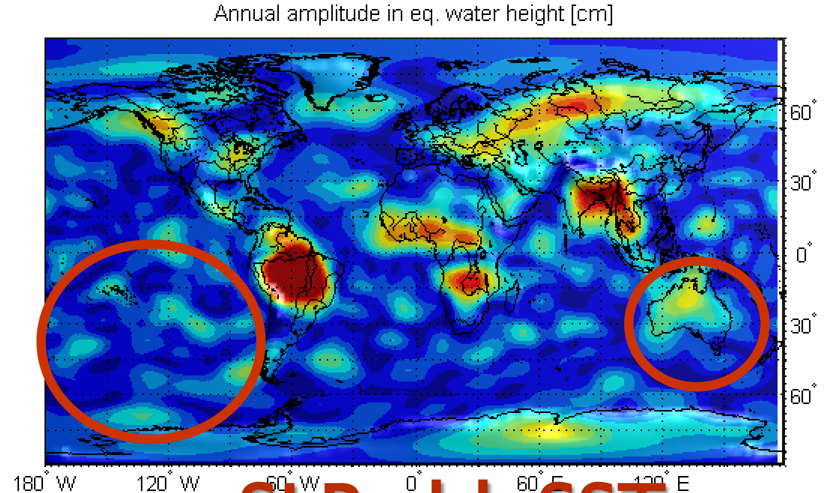
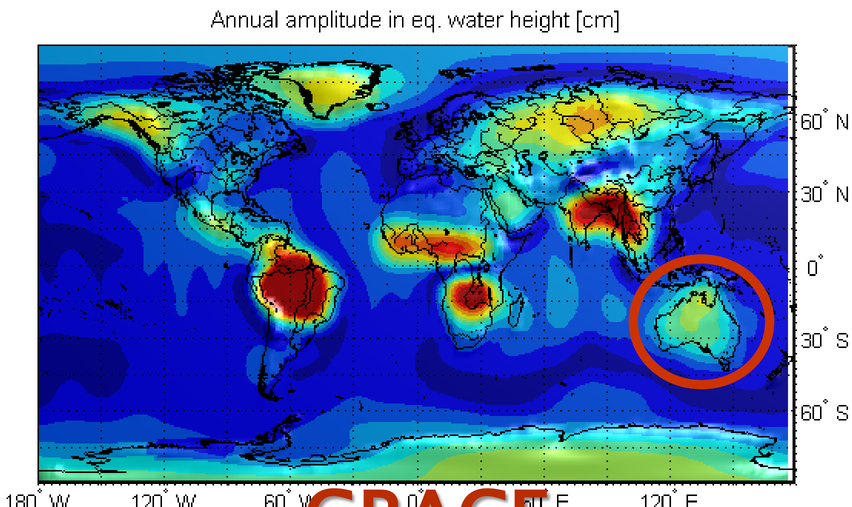
GRACE vs. hl-SST vs. SLR+hl-SST



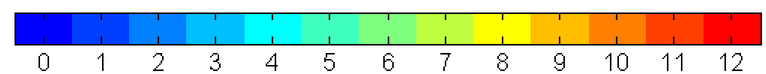
hl-SST



SLR+hl-SST



GRACE



Combination of hl-SST solutions with SLR reduces the variations over oceans and some spurious signals.

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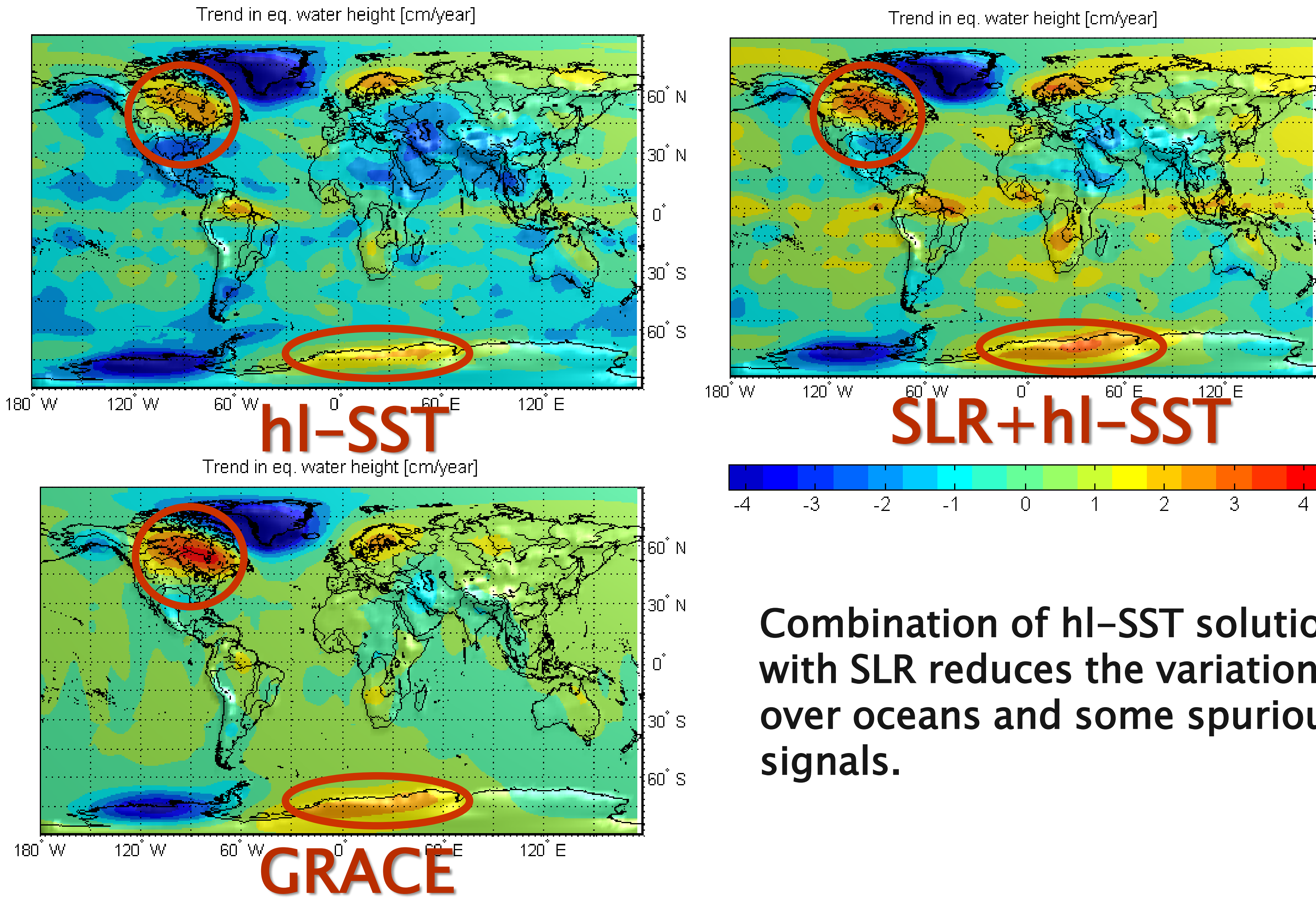
GRACE vs. hl-SST vs. SLR+hl-SST



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Summary

Low degree gravity field parameters can be well derived from SLR observations to geodetic satellites. Low-degree SH provide information about large-scale mass transport in the system Earth.

The mean difference of seasonal signal for low degree SH between SLR-only and GRACE K-band is 7.5E-12, i.e., 23% of mean total annual signal. It implies that the agreement between SLR and GRACE is at 77% level by means of low degree SH.

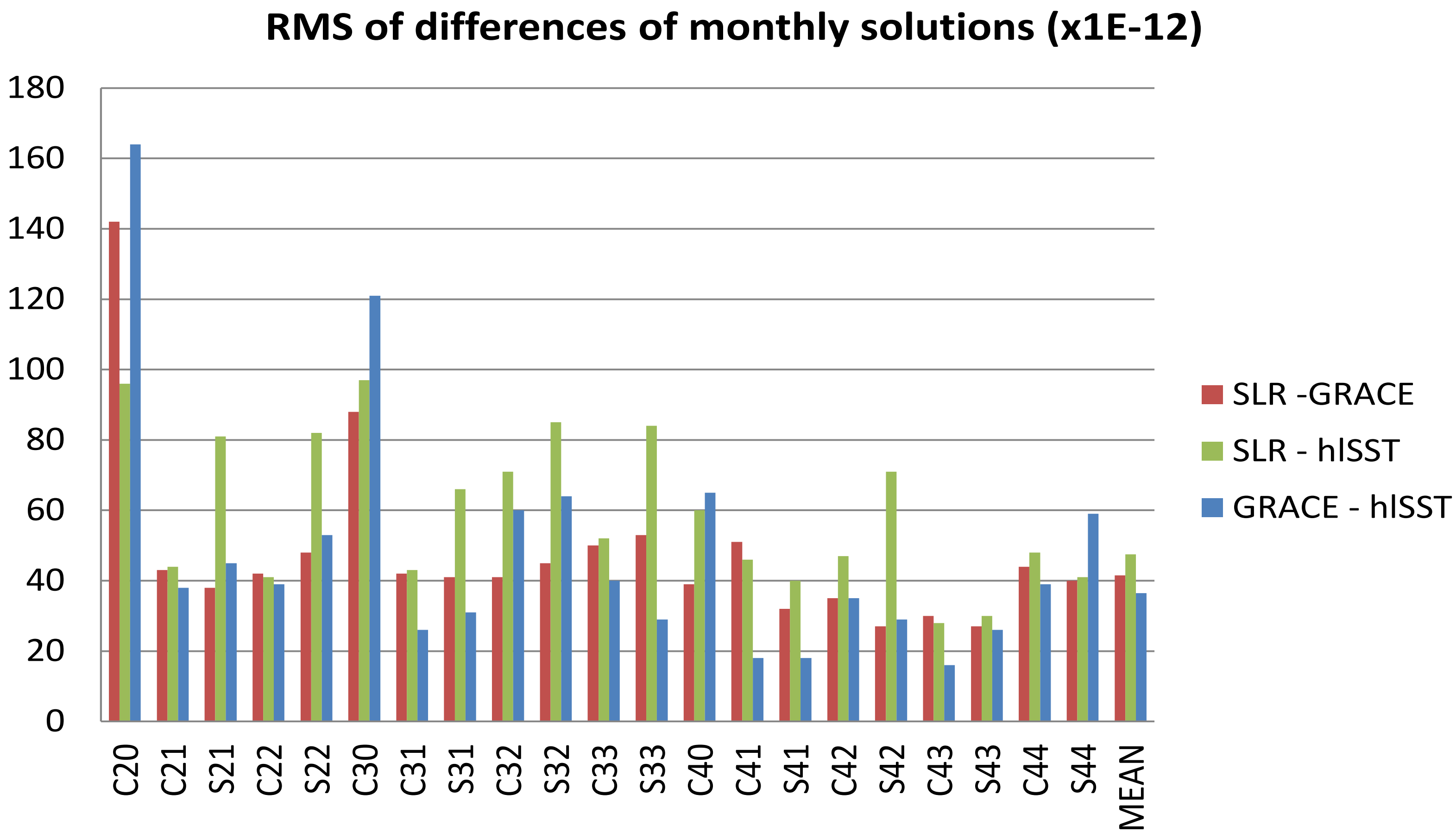
The combination SLR + hl-SST provides information about mass transport in the system Earth with higher spatial resolution w.r.t. SLR-only solutions.

The AIUB SLR-only temporal gravity field solutions will be published soon on ICGEM website.

Thank you
for your attention

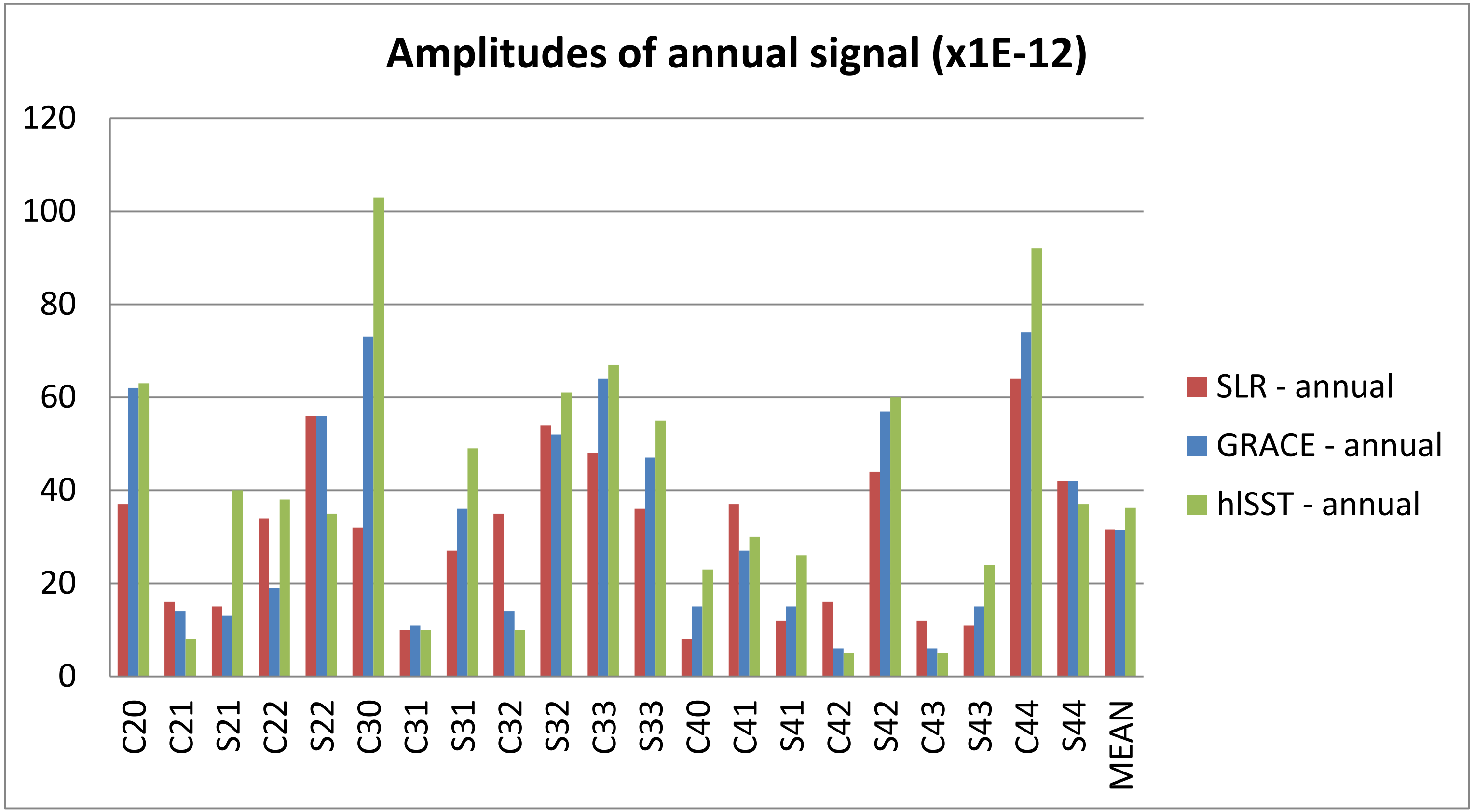
Back-up slides

Comparison of hlSST+SLR w.r.t. GRACE



The mean RMS of differences between estimated SH coefficients are: 41, 47, and 36.E-12 for SLR vs.GRACE, SLR vs.hlSST+SLR, and GRACE vs. hlSST+SLR, respectively.

Comparison of hlSST+SLR w.r.t. GRACE



In hlSST solutions the amplitudes are overestimated by about 12%.

The RMS of differences between estimated amplitudes are 7.5, 9.0, and 13.9E-12 for SLR-GRACE, SLR-hlSST, and GRACE-hlSST, respectively.

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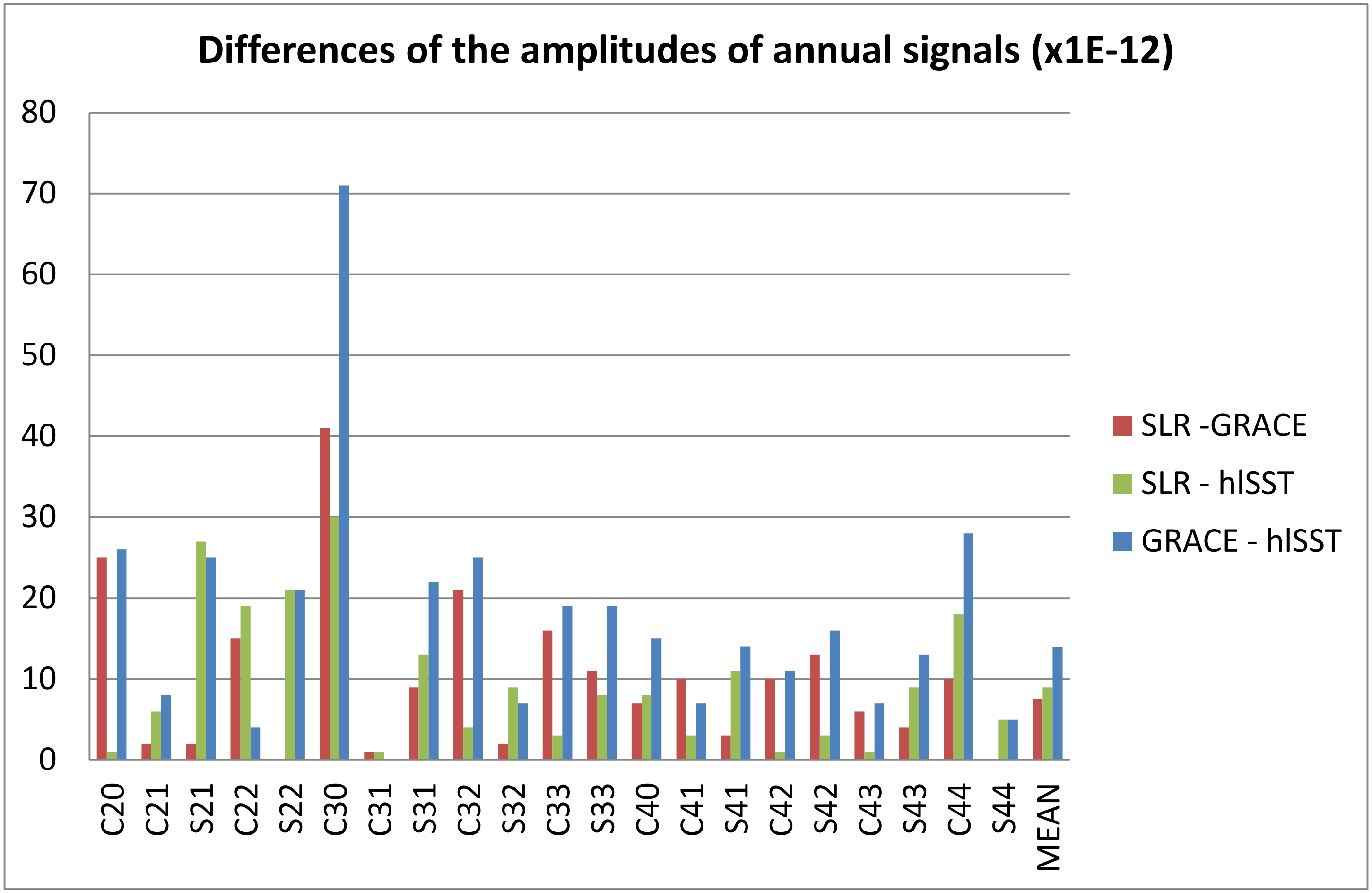
Comparison of hlSST+SLR w.r.t. GRACE



hlSST denotes hlSST+SLR

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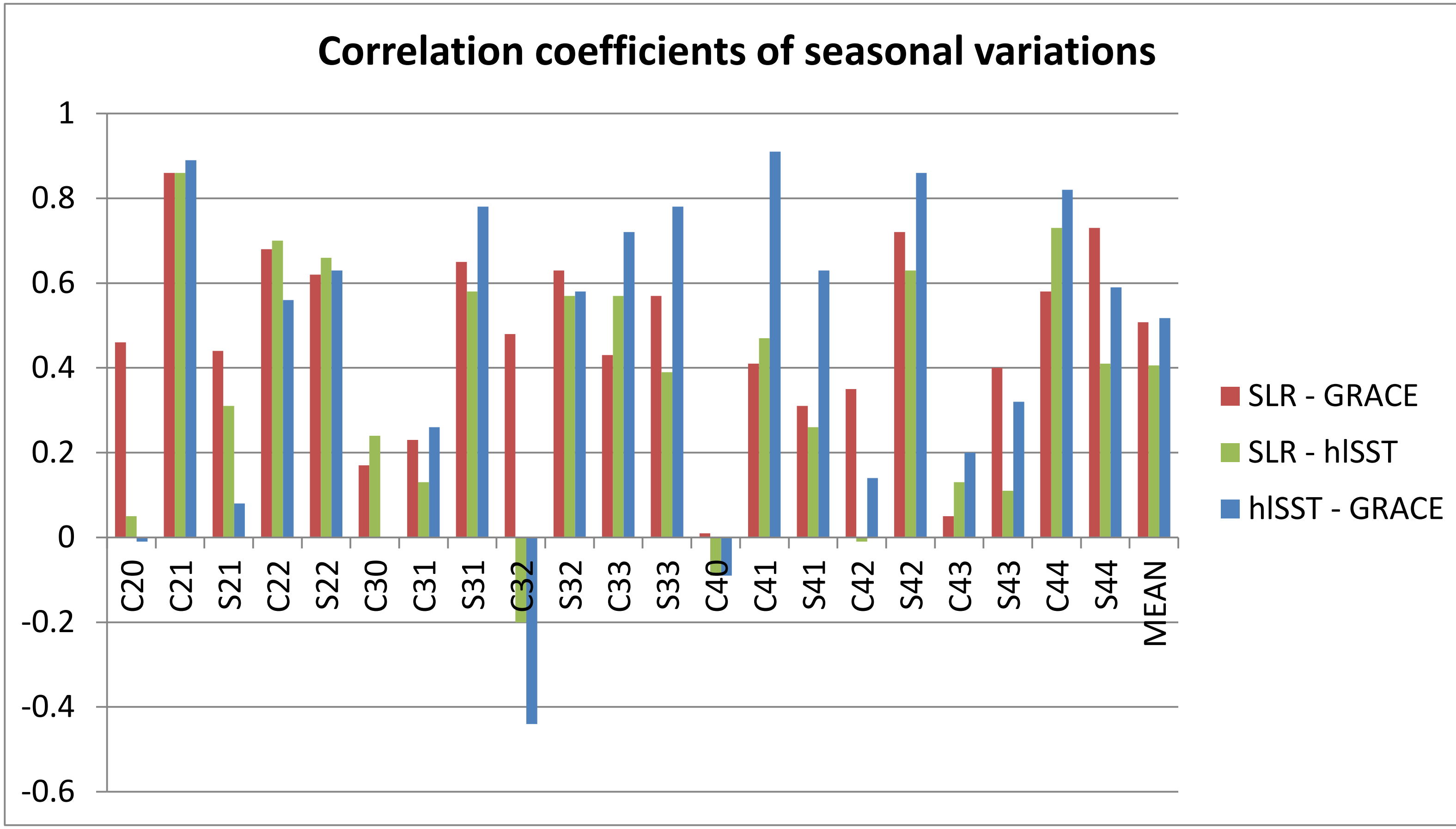
Comparison of hlSST+SLR w.r.t. GRACE



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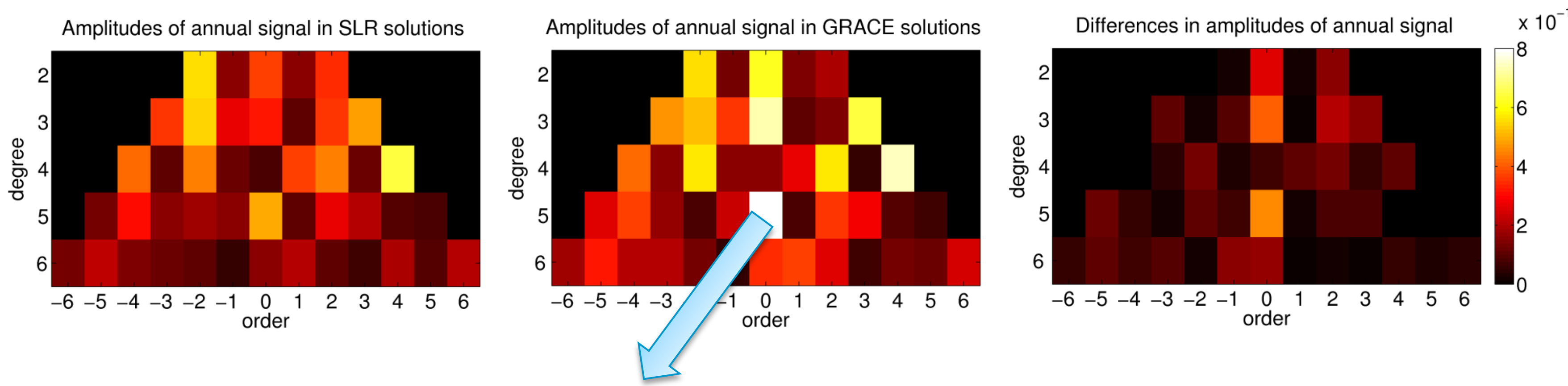
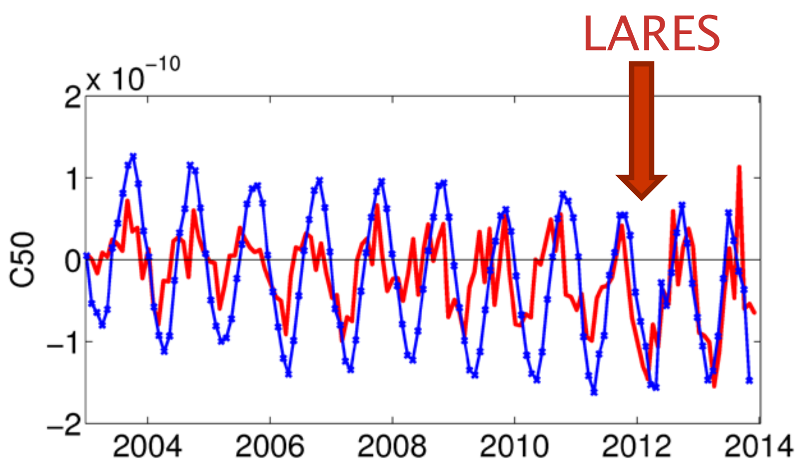
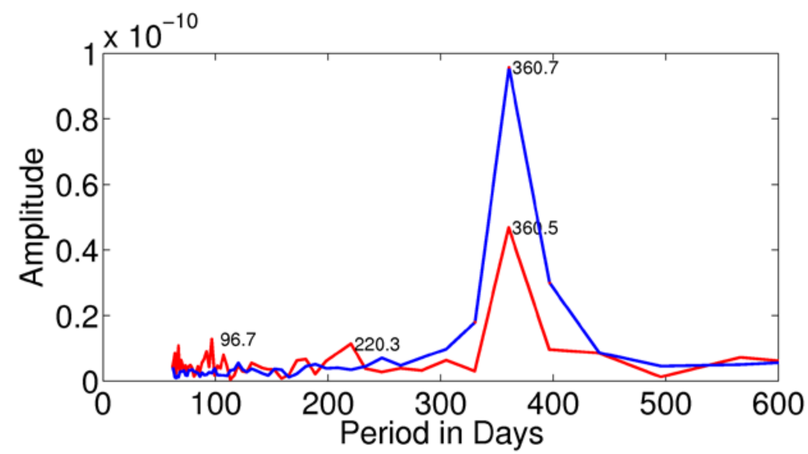
Comparison of SLR w.r.t. GRACE







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Comparison of hlSST+SLR w.r.t. GRACE

Amplitudes of annual signal (x1E-12)		
	Mean (up to d/o 4/4)	Mean without zonals
SLR	30.8	31.5
GRACE	34.2	31.6
hlSST+SLR	40.0	36.2
Mean differences of annual amplitudes (x1E-12)		
SLR – GRACE	9.9	7.5
SLR – hlSST+SLR	9.6	9.0
GRACE – hlSST+SLR	17.3	13.9
Mean correlation coefficients		
SLR – GRACE	0.47	0.51
SLR – hlSST+SLR	0.36	0.41
GRACE – hlSST+SLR	0.44	0.52
RMS of differences (x1E-12)		
SLR – GRACE	42	41
SLR – hlSST+SLR	52	47
GRACE – hlSST+SLR	39	36

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SLR Satellite 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 (∼ min)	$0.8 \cdot 10^{-14}$	$3.0 \cdot 10^{-11}$	$2.6 \cdot 10^{-12}$	$5.0 \cdot 10^{-11}$
· Atmospheric drag (∼ max)	$2.0 \cdot 10^{-13}$	$5.9 \cdot 10^{-10}$	$4.8 \cdot 10^{-11}$	$5.0 \cdot 10^{-8}$

AJISAI:

- Diameter: 2.15 m
- Mass: 685 kg
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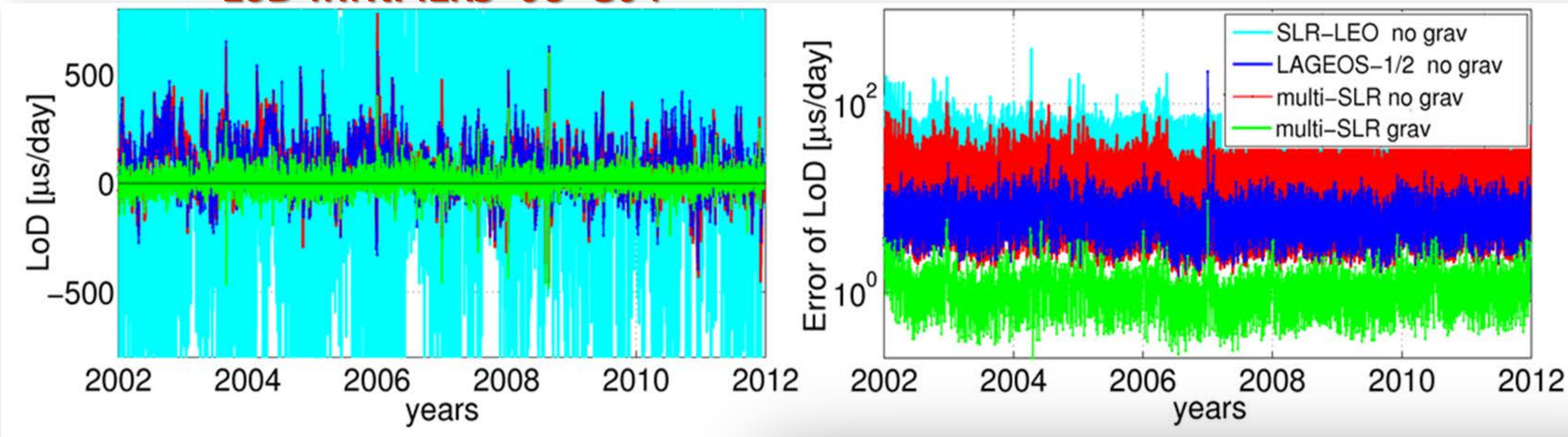
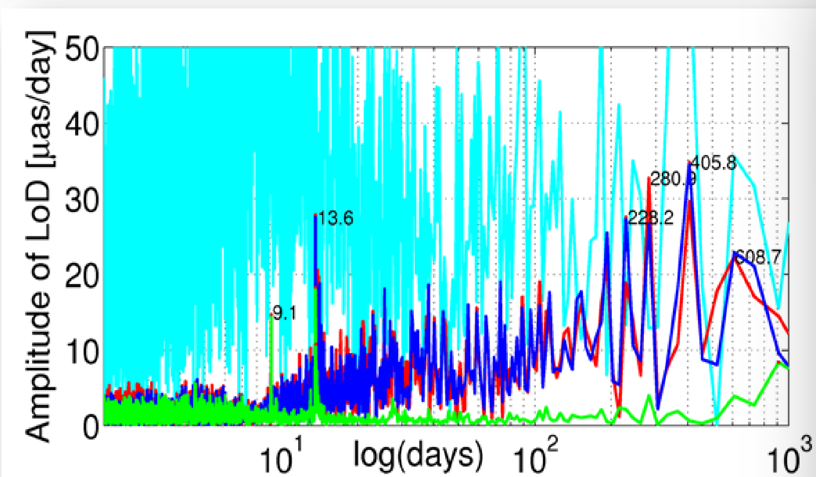
SLR solution with and without estimating gravity field

LoD w.r.t. IERS-08-C04





For LoD, the simultaneous estimation of the gravity field parameters:

- 1. reduces the offset of LoD estimates,
- 2. substantially reduces the a posteriori error of estimated LoD. The mean a posteriori error of LoD is 1.3, 16.9, 7.1, and 44.6 µs/day in the multi-SLR solution with gravity, multi-SLR solution without gravity, LAGEOS-1/2 solution without gravity, and SLR-LEO solution without gravity field parameters, respectively.
- 2. reduces peaks in the spectral analysis, which correspond, e.g., to orbit modeling deficiencies (peaks of 222 days, i.e., draconitic year of LAGEOS-2, 280 days, i.e., eclipsing period of LAGEOS-1),

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Estimated parameters of SLR satellites

Satellite	Nominal CoM [mm]	Estimated CoM [mm]	Error [mm]
Starlette	75	77.8	3.1
Stella	75	77.8	3.1
Blits	-209.6	-205.7	8.5
Larets	56.2	63.1	5.5
LARES	133	133.6	2.1
Beacon-C	no data	276.5	4.8
Beacon-C (N hemisphere)	no data	285.1	4.9
Beacon-C (S hemisphere)	no data	220.7	6.7

Due to the lack of information about the parameters of Beacon-C, the center-of-mass corrections had to be estimated on a basis of in-orbit analysis. A significant difference was found in CoM for SLR stations located in Southern and Northern hemispheres.
Estimated area-to-mass for Beacon-C: A/m = $1.75 \pm 0.2 \cdot 10^{-2}$ $m^2\ kg^{-1}$

For Larets, a significant difference w.r.t. nominal CoM was found.