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

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Satellite Laser Ranging (SLR)

- SLR provides very precise (at a few mmlevel) 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



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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-perrevolution empirical accelerations in out-of-plane (due to correlations with C20).
- 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	AllSAI :			
)rbits	Osculating elements Dynamical parameters	a, e, i, Ω , ω , u_0 (LAGEOS: 1 set per 10 days, LEO: 1 set per 1 day) 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	 Diameter: 2.15 Mass: 685 kg Area-to-mass: A/m: 58·10⁻⁴ m² kg⁻¹ LAGEOS : Diameter: 0.60 m Mass: 407 kg 			
U	Pseudo-stochastic pulses	(1 set per day) LAGEOS-1/2 : no pulses Sta/Ste/AJI : once-per-revolution in along-track only	 A/m: 6.9·10⁻⁴ m²kg⁻¹ LARES : Diameter: 0.36 m 			
Earth rotation parameters		X _P , Y _P , UT1-UTC (Piecewise linear, 1 set per day)	A/m: $2.7 \cdot 10^{-4} \text{ m}^2 \text{ kg}^{-1}$			
Geocenter coordinates		1 set per 30 days	Beacon-C:			
Earth gravity field		Estimated up to d/o 10/10 (1 set per 30 days)	 Mass: 32 kg Center-of-mass correction: unknown 			
Station coordinates		1 set per 30 days	Area-to-mass: unknown BUT: due to low inclination (41°) and			
Other parameters		Range biases for all stations (LEO) and for selected stations (LAGEOS)	large eccentricity (0.023) , this satellite can be used for decorrelation of some gravity field parameters.			





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Processing scheme



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Sensitivity of SLR satellites to SH coefficients



- 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.





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)





SLR-only solutions



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SLR–only solutions



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Combined SLR + hl-SST solutions





Combination of hISST and SLR



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

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SLR+hl-SST solutions



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

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Annual amplitude in eq. water height [cm]

Annual amplitude in eq. water height [cm]



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



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

Trend in eq. water height [cm/year]



Trend in eq. water height [cm/year]



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

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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







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. hISST+SLR, respectively.







In hISST 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-hISST, and GRACE-hISST, respectively.



hISST denotes hISST+SLR



hISST denotes hISST+SLR



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				
hISST+SLR	40.0	36.2				
Mean differences of annual amplitudes (x1E-12)						
SLR – GRACE	9.9	7.5				
SLR – hISST+SLR	9.6	9.0				
GRACE – hISST+SLR	17.3	13.9				
Mean correlation coefficients						
SLR – GRACE	0.47	0.51				
SLR – hISST+SLR	0.36	0.41				
GRACE – hISST+SLR	0.44	0.52				
RMS of differences (x1E–12)						
SLR – GRACE	42	41				
SLR – hISST+SLR	52	47				
GRACE – hISST+SLR	39	36				



-satellite

SLR Satellite Sensitivity to Gravity Field

Perturbing accel.	Accel. on LAGEOS	Accel. on AJISAI	Accel. on LARES	Accel. on Stella
Gravitational perturbations:				
\cdot Earth's monopole	2.7	6.4	6.5	7.7
\cdot Earth's oblateness C_{20}	$1.0\cdot 10^{-3}$	$6.2\cdot 10^{-3}$	$6.3\cdot 10^{-3}$	$8.8\cdot 10^{-3}$
· Low-order grav. C_{22}	$6.0\cdot 10^{-6}$	$3.6\cdot 10^{-5}$	$3.7\cdot 10^{-5}$	$5.1\cdot 10^{-5}$
\cdot Low-order grav. C_{66}	$8.6\cdot 10^{-8}$	$3.1\cdot 10^{-6}$	$3.2\cdot 10^{-6}$	$6.3\cdot 10^{-6}$
\cdot Mid-order grav. C_{2020}	$8.1\cdot 10^{-13}$	$1.5\cdot 10^{-8}$	$1.6\cdot 10^{-8}$	$1.1\cdot 10^{-7}$
\cdot Grav. attr. of Moon	$2.1\cdot 10^{-6}$	$1.4\cdot 10^{-6}$	$1.4\cdot 10^{-6}$	$1.3\cdot 10^{-6}$
\cdot Grav. attr. of Sun	$9.6\cdot 10^{-7}$	$6.4\cdot 10^{-7}$	$6.5\cdot 10^{-7}$	$5.7\cdot 10^{-7}$
\cdot Grav. attr. of Venus	$1.3\cdot 10^{-10}$	$8.5\cdot 10^{-11}$	$8.5\cdot 10^{-11}$	$7.8\cdot 10^{-11}$
\cdot Solid Earth tides	$3.7\cdot 10^{-6}$	$2.0\cdot 10^{-5}$	$2.0\cdot 10^{-5}$	$2.9\cdot 10^{-5}$
\cdot Ocean tides	$3.7\cdot 10^{-7}$	$1.9\cdot 10^{-6}$	$2.0\cdot 10^{-6}$	$3.0\cdot 10^{-6}$
General relativity:				
\cdot Schwarzschild effect	$2.8\cdot 10^{-9}$	$1.1\cdot 10^{-8}$	$1.1\cdot 10^{-8}$	$1.4\cdot 10^{-8}$
\cdot Lense-Thirring effect	$2.7\cdot 10^{-11}$	$1.3\cdot 10^{-10}$	$1.4\cdot 10^{-10}$	$1.8\cdot 10^{-10}$
\cdot 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:				
\cdot Solar radiation pressure	$3.5\cdot 10^{-9}$	$2.5\cdot 10^{-8}$	$1.1\cdot 10^{-9}$	$4.4\cdot 10^{-9}$
\cdot Earth radiation pressure	$4.4\cdot 10^{-10}$	$8.6\cdot 10^{-9}$	$3.9\cdot 10^{-10}$	$1.8\cdot 10^{-9}$
\cdot Thermal re-radiation	$5.0\cdot 10^{-11}$	$4.1\cdot 10^{-10}$	$1.9\cdot 10^{-11}$	$6.9\cdot 10^{-11}$
\cdot Light aberration	$1.1\cdot 10^{-13}$	$1.1\cdot 10^{-12}$	$5.1\cdot 10^{-14}$	$2.0\cdot 10^{-13}$
\cdot Atmospheric drag (~ min)	$0.8\cdot 10^{-14}$	$3.0\cdot 10^{-11}$	$2.6\cdot 10^{-12}$	$5.0\cdot10^{-11}$
\cdot Atmospheric drag (~ max)	$2.0\cdot 10^{-13}$	$5.9 \cdot 10^{-10}$	$4.8\cdot10^{-11}$	$5.0\cdot 10^{-8}$



Area-to-mass: A/m: 6.9·10⁻⁴ m² kg⁻¹

LARES:

- Diameter: 0.36 m
- Mass: 387 kg
- Area-to-mass: A/m: 2.7·10⁻⁴ m² kg⁻¹



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SLR solution with and without estimating gravity field





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 = $1.75 \pm 0.2 \cdot 10^{-2} \text{ m}^2 \text{ kg}^{-1}$

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