Consistent estimation of station coordinates, Earth orientation parameters and selected low degree Earth's gravity field coefficients from SLR measurements

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Ocean Surface Topography Science Team Meeting (OSTST) 2017,
October 23-27, 2017, Miami, Florida, United States of America

Introduction

- Precise geodetic parameters such as ***positions*** of crust-fixed geodetic tracking stations (TRF), ***Earth orientation parameters*** (EOP) and Stokes coefficients of the ***Earth's gravity field*** model are the basis for positioning, navigation and monitoring of dynamic processes on the Earth and in space.
- Up to now, these parameter groups are estimated separately.
- The SLR constellation used in this study comprises ***up to 11 geodetic satellites*** with different orbit characteristics and allows a common estimation of all parameters.

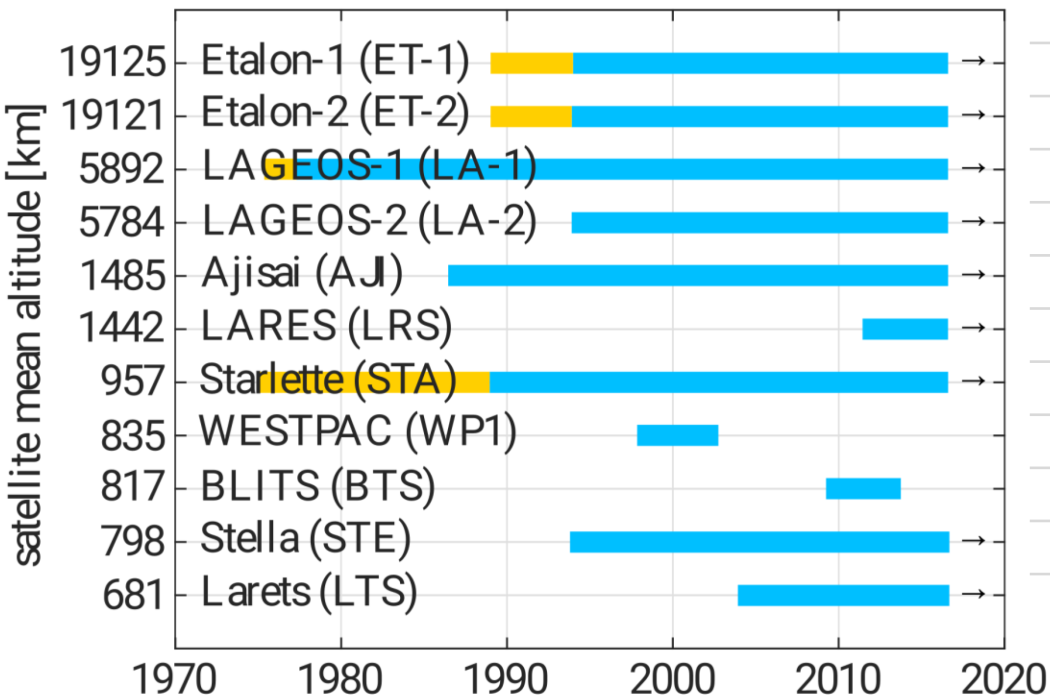
➢ **Which satellite constellation yields optimum results for the estimated parameters?**

➢ Within this presentation, we address the following points:

- Decorrelation of parameter groups in the normal equation (NEQ)
- Determination of terrestrial reference frames (TRF) and Earth orientation parameters (EOP)
- Sensitivity of SLR observations to the coefficients of the Earth's gravity field model (GFC)
- Improvement of the estimated GFC by using additional satellites

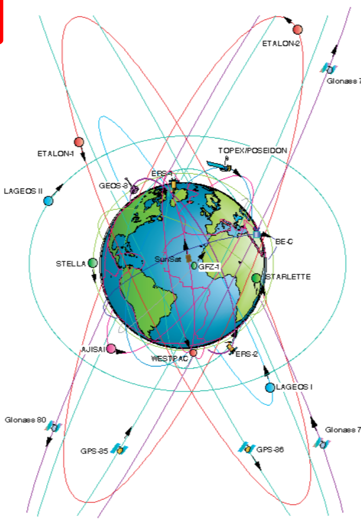
SLR multi-satellite solution

- SLR observations to up to 11 geodetic satellites in different orbits (1979–2017)
- Combination of single-satellite solutions on the normal equation level



Inclination [deg]
65.3
64.4
109.8
52.7
50.0
69.5
49.8
98.8
98.7
98.4
98.0

Current ILRS standard setup



- ➢ Comparison of the 4-satellite standard solution to several 5-satellite solutions and a solution combined from all 11 satellites
- ➢ We used the DOGS software developed at DGFI-TUM

Estimated parameters

- Weekly 3-D station Cartesian coordinates
- Daily EOP (x_{Pol} , y_{Pol} , ΔLOD)
- Selected weekly Stokes coefficients up to degree 6

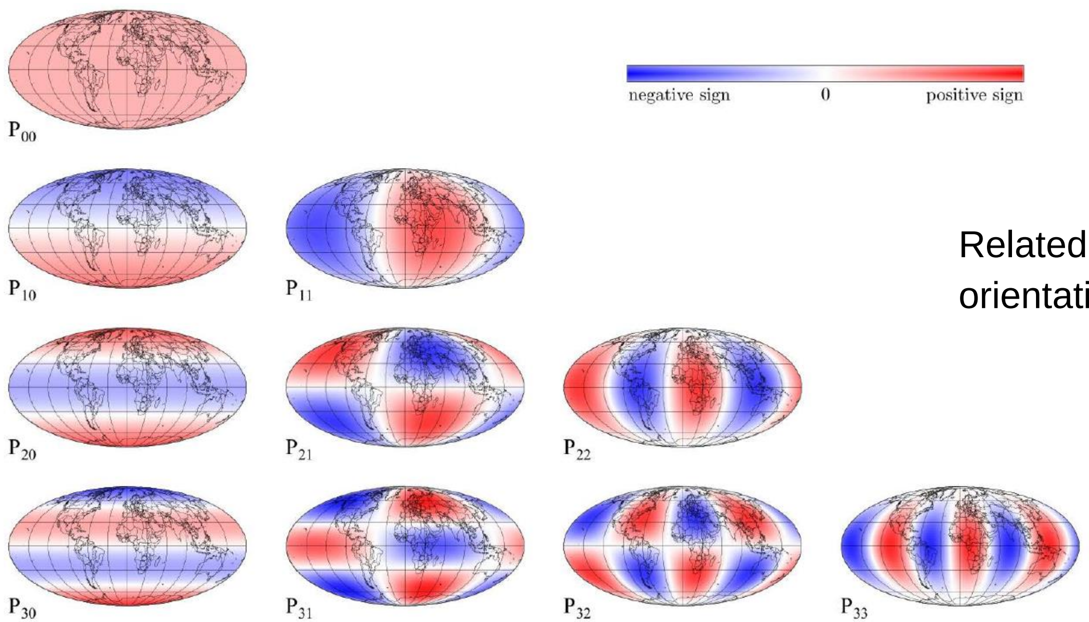
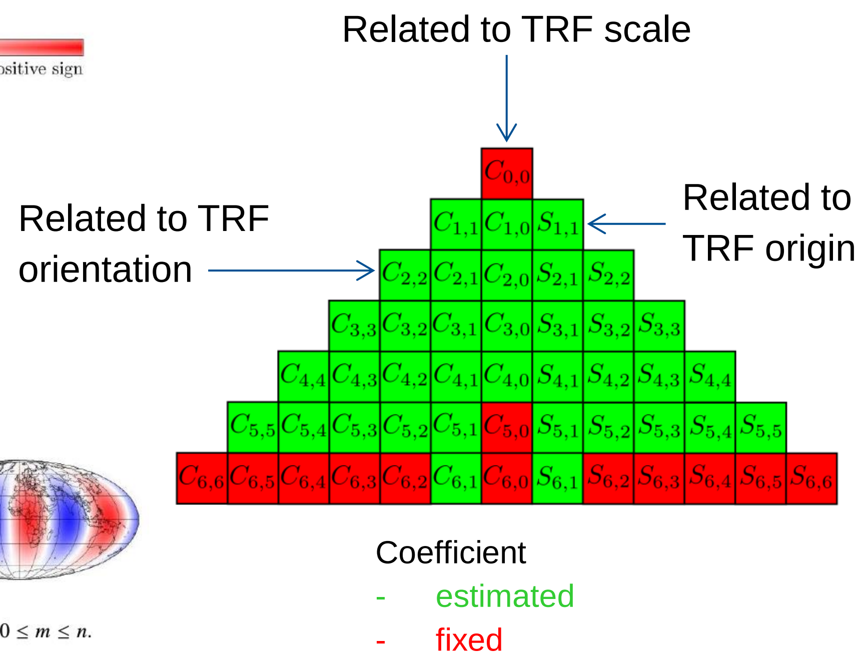


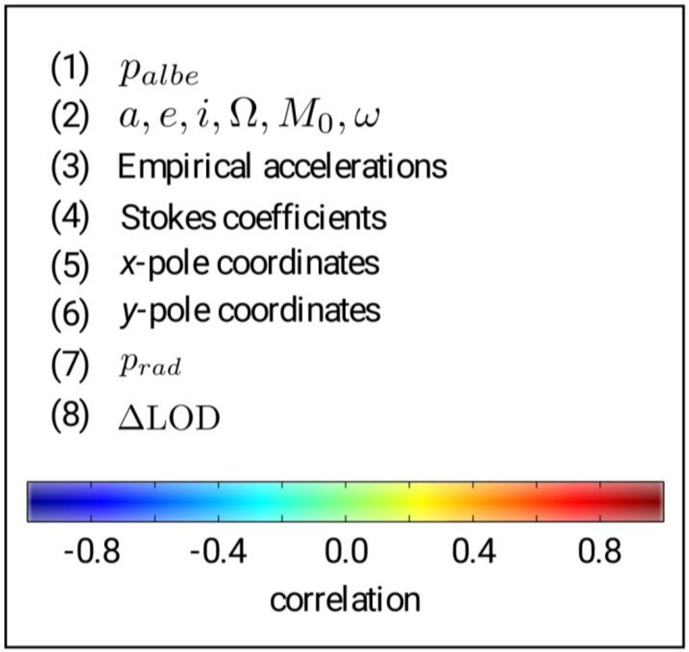
Figure 3.4: Laplace's fully normalized surface spherical harmonic functions of degree $0 \leq n \leq 3$ and order $0 \leq m \leq n$.

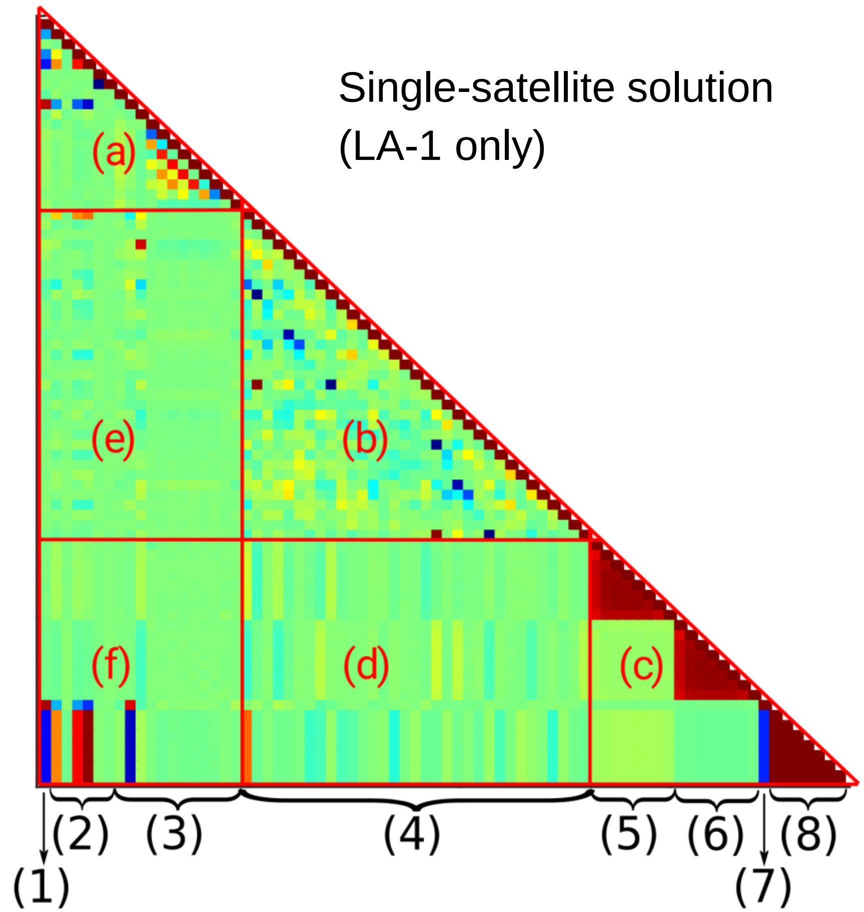


From: Bloßfeld M. (2015): **The key role of Satellite Laser Ranging towards the integrated estimation of geometry, rotation and gravitational field of the Earth.** Dissertation, Technische Universität München and Reihe C der Deutschen Geodätischen Kommission. ISBN: 978-3-7696-5157-7

Correlations between parameters

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



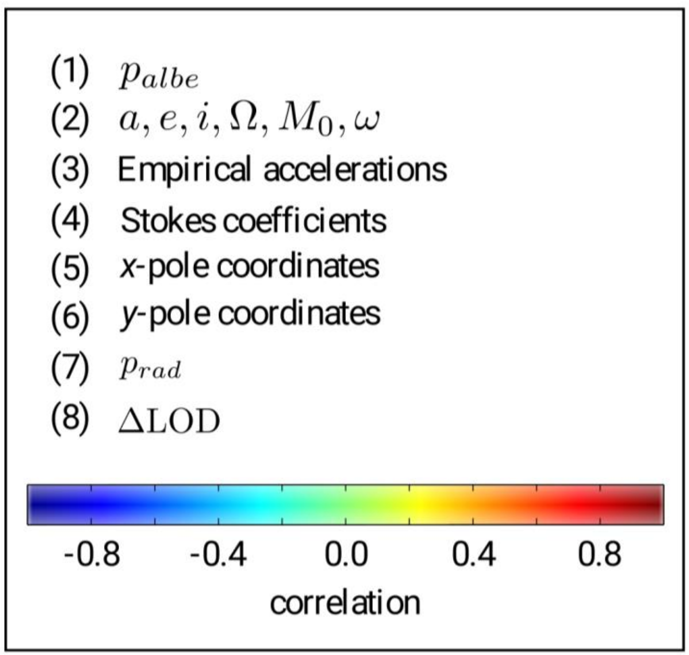


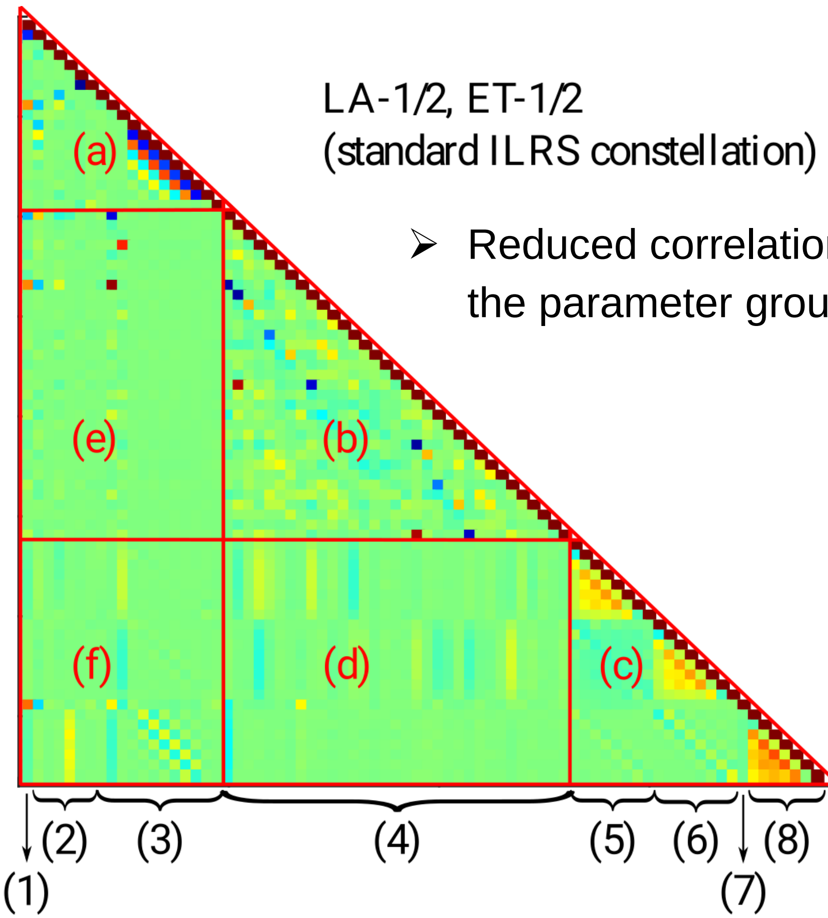
Single-satellite solution
(LA-1 only)

(a) orbital elements and p_{albe}
(b) Stokes coefficients
(c) EOP and SRP scaling factor (p_{rad})
(d), (e), (f) correlations between parameter groups

Correlations between parameters

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



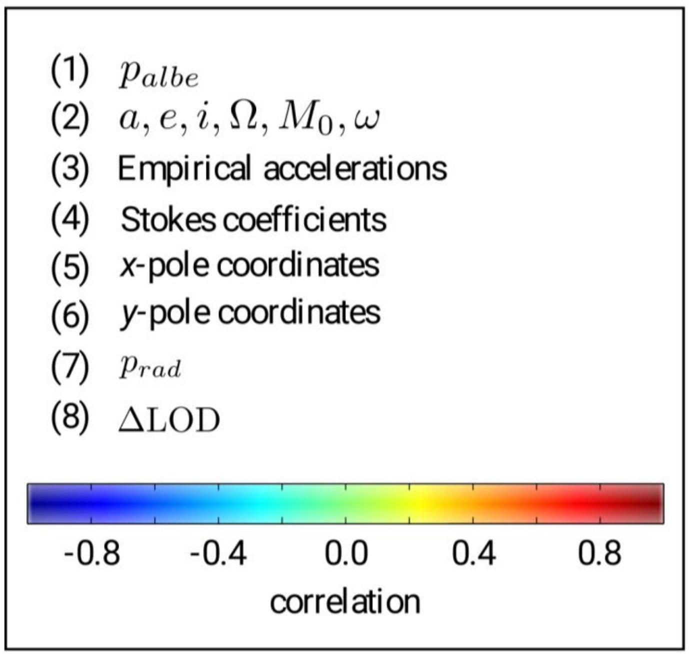


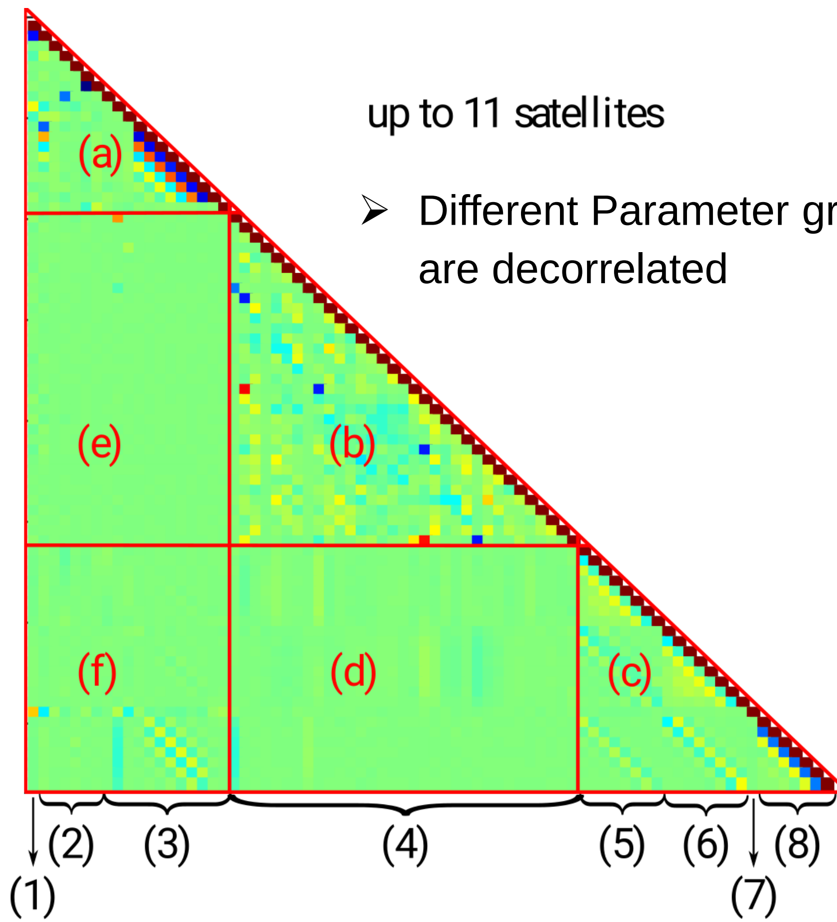
- Reduced correlations of the parameter groups

(a) orbital elements and p_{albe}
(b) Stokes coefficients
(c) EOP and SRP scaling factor (p_{rad})
(d), (e), (f) correlations between parameter groups

Correlations between parameters

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





up to 11 satellites

- Different Parameter groups are decorrelated

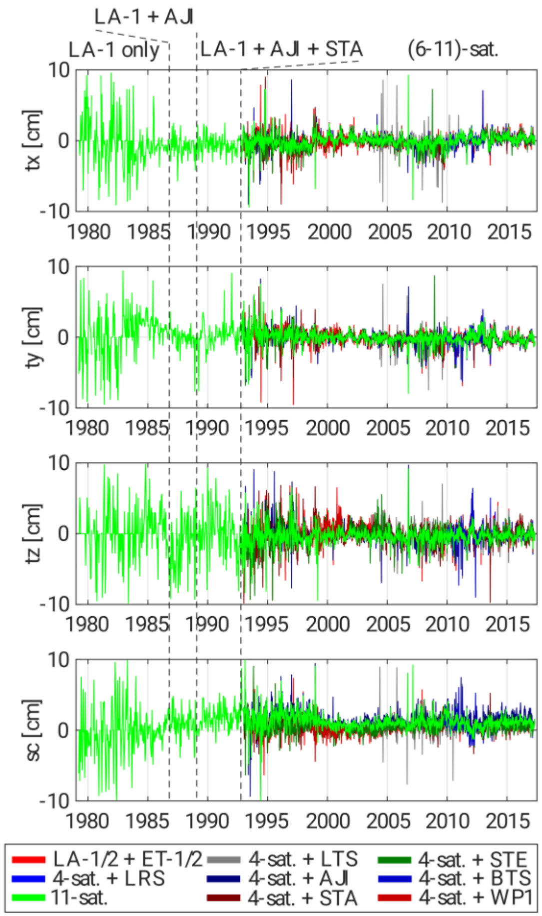
(a) orbital elements and p_{albe}

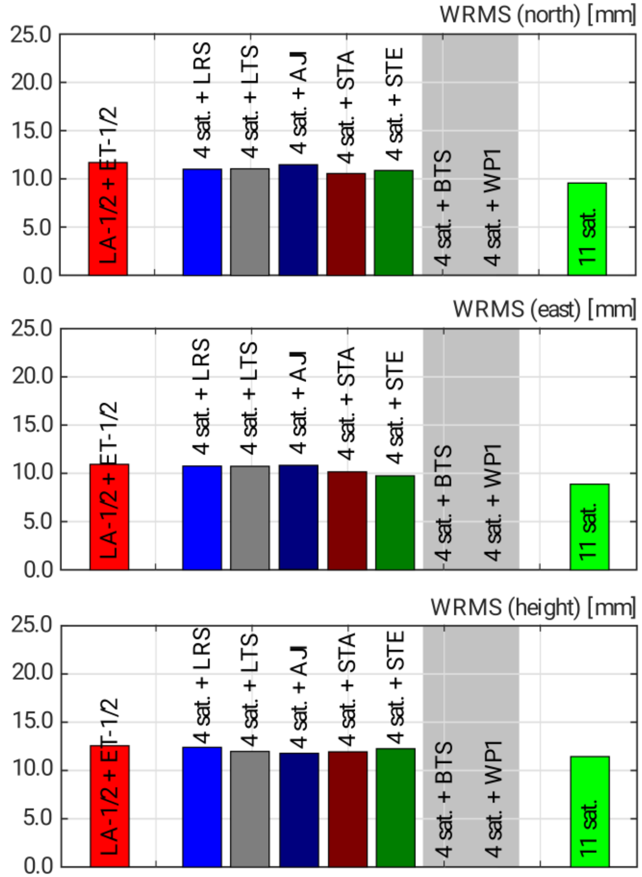
(b) Stokes coefficients

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

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

Results: Terrestrial Reference Frames

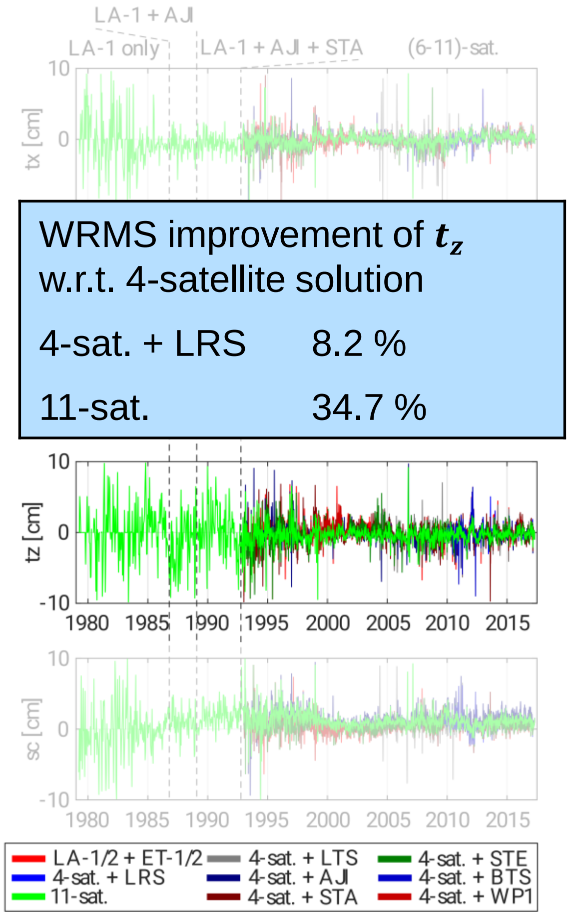




Weekly 7-parameter Helmert transformation w.r.t. SLRF2014

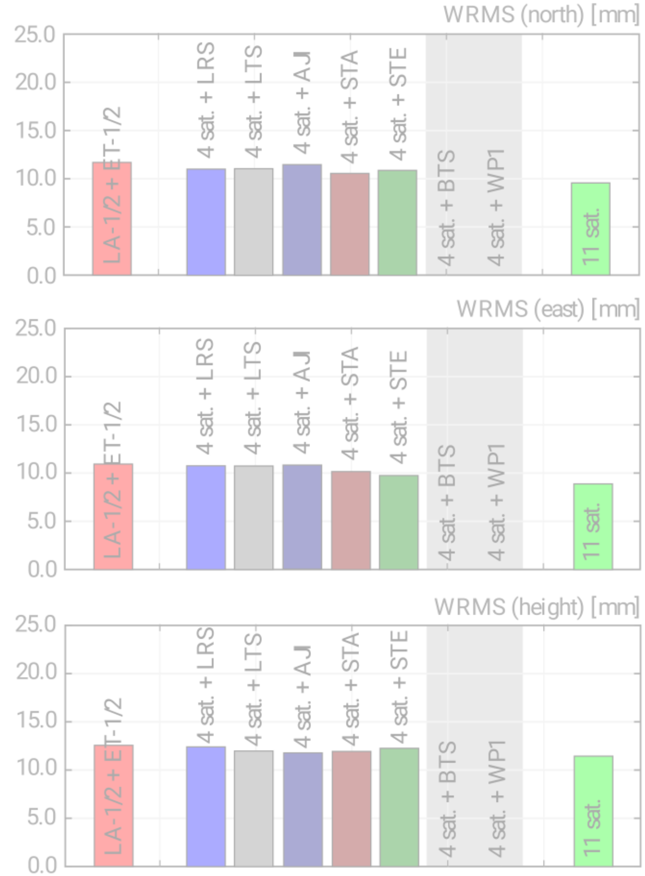
- Left: reduction of the scatter of TRF datum parameters by up to 35 %
- Right: WRMS of the transformation residuals reduced by up to 22 %

Results: Terrestrial Reference Frames



WRMS improvement of t_z w.r.t. 4-satellite solution

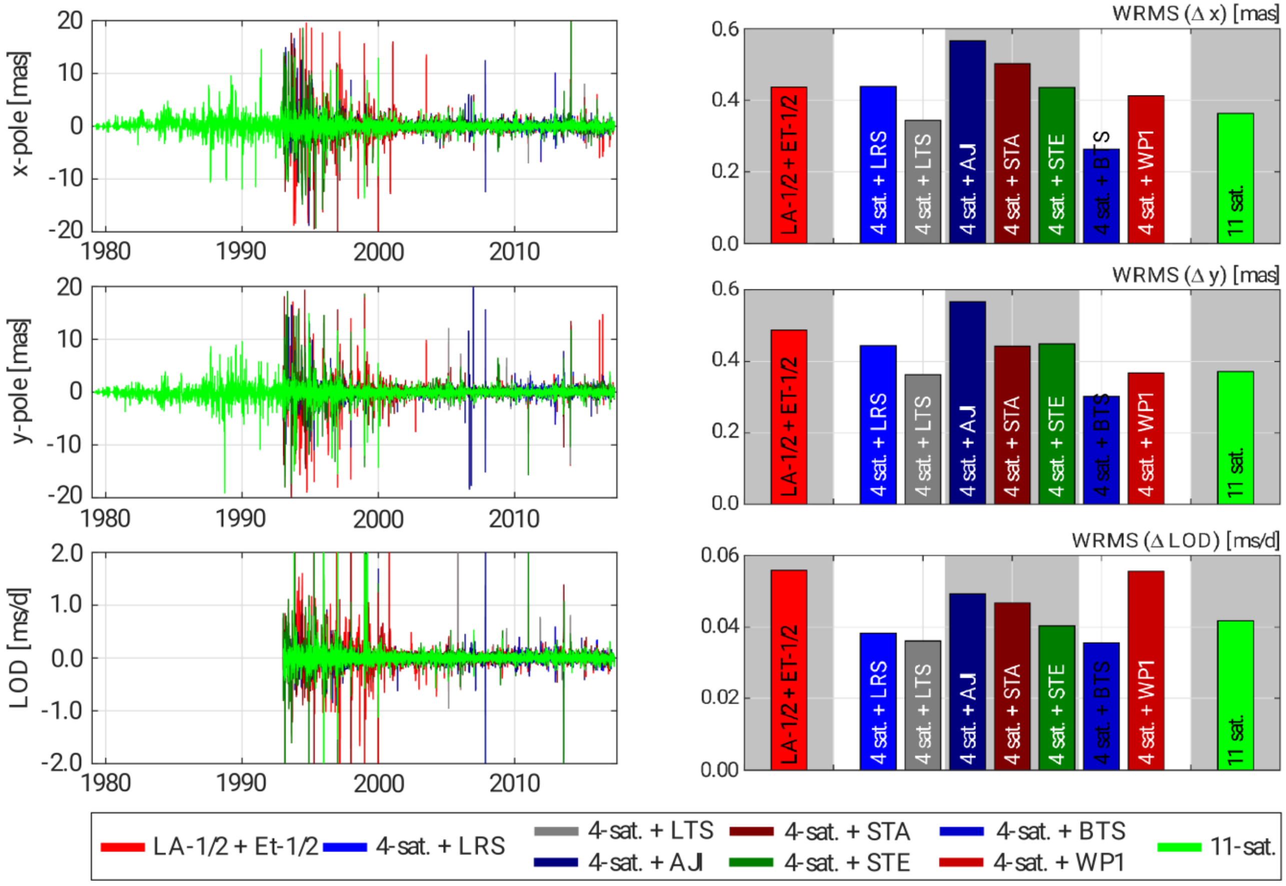
4-sat. + LRS	8.2 %
11-sat.	34.7 %



Weekly 7-parameter Helmert transformation w.r.t. SLRF2014

- ➢ Left: reduction of the scatter of TRF datum parameters by up to 35 %
- ➢ Right: WRMS of the transformation residuals reduced by up to 22 %

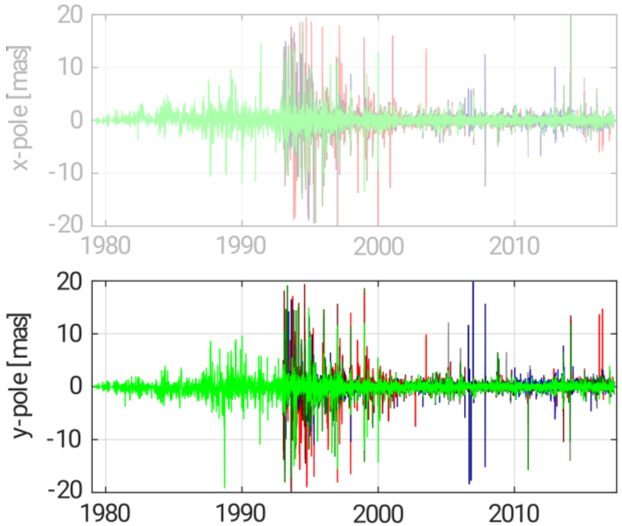
Results: Earth Orientation Parameters

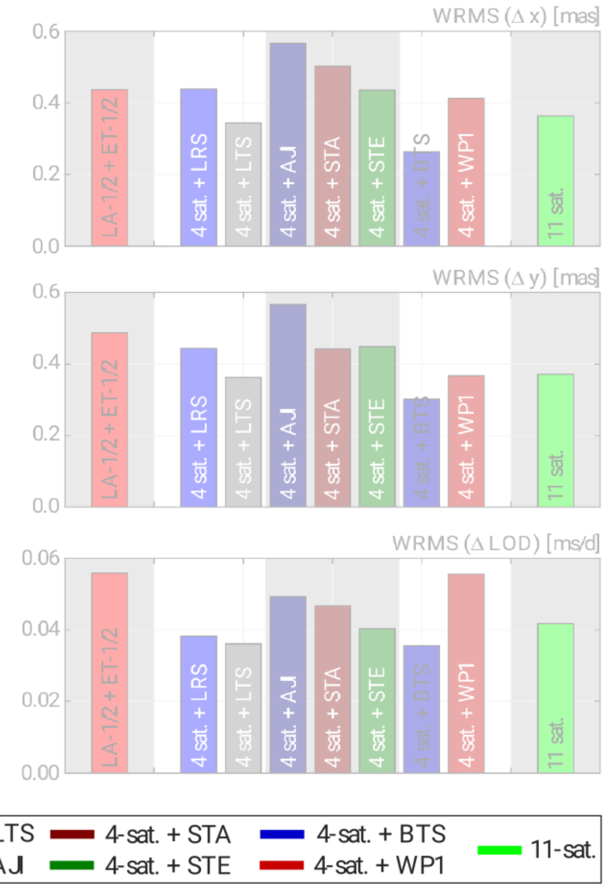


Differences of estimated EOP w.r.t. IERS 08 C04

- WRMS of the EOP reduced by up to 26 %
- Weighted mean value reduced by up to 96 %

Results: Earth Orientation Parameters





WRMS improvement of y_{pole}
w.r.t. 4-satellite solution

4-sat. + LRS	0.8 %
11-sat.	21.2 %

Differences of estimated EOP w.r.t. IERS 08 C04

- WRMS of the EOP reduced by up to 26 %
- Weighted mean value reduced by up to 96 %

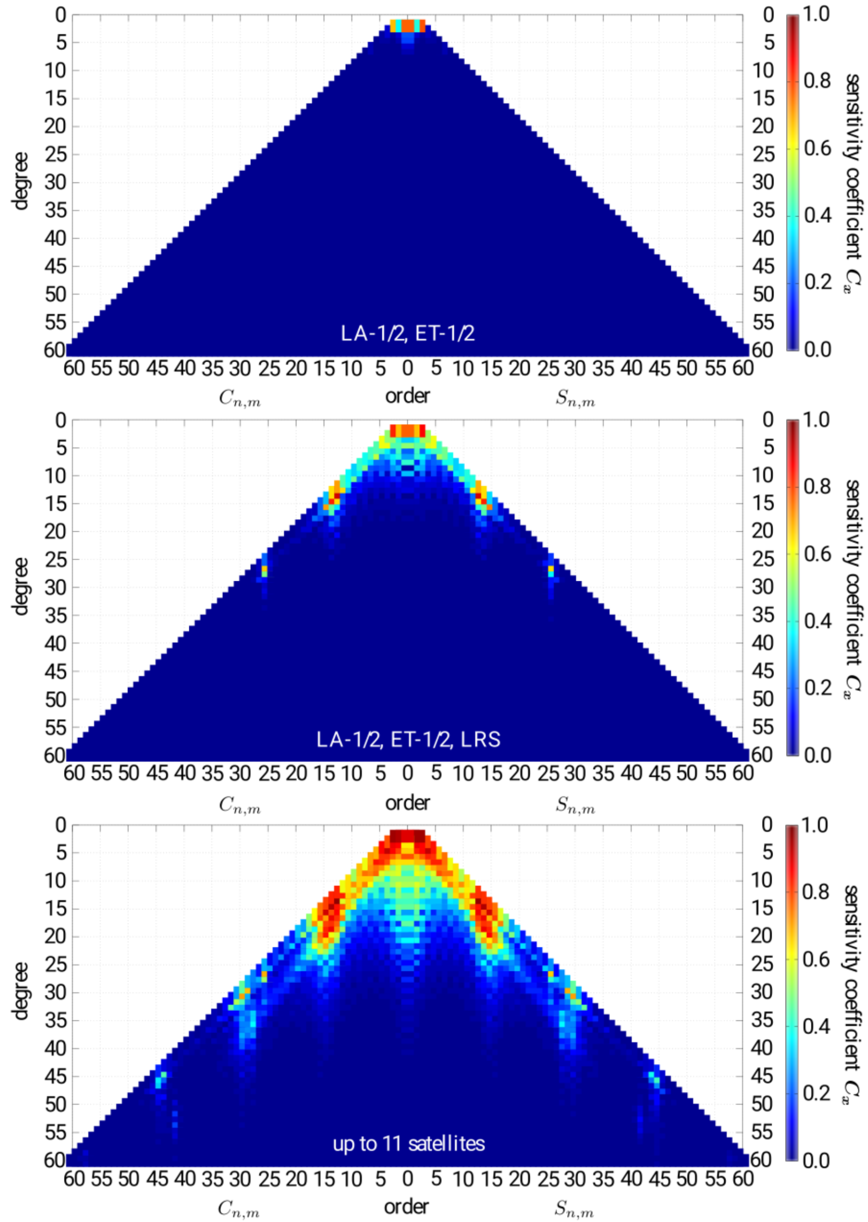
Sensitivity analysis

Sensitivity of the observations to gravity field coefficients

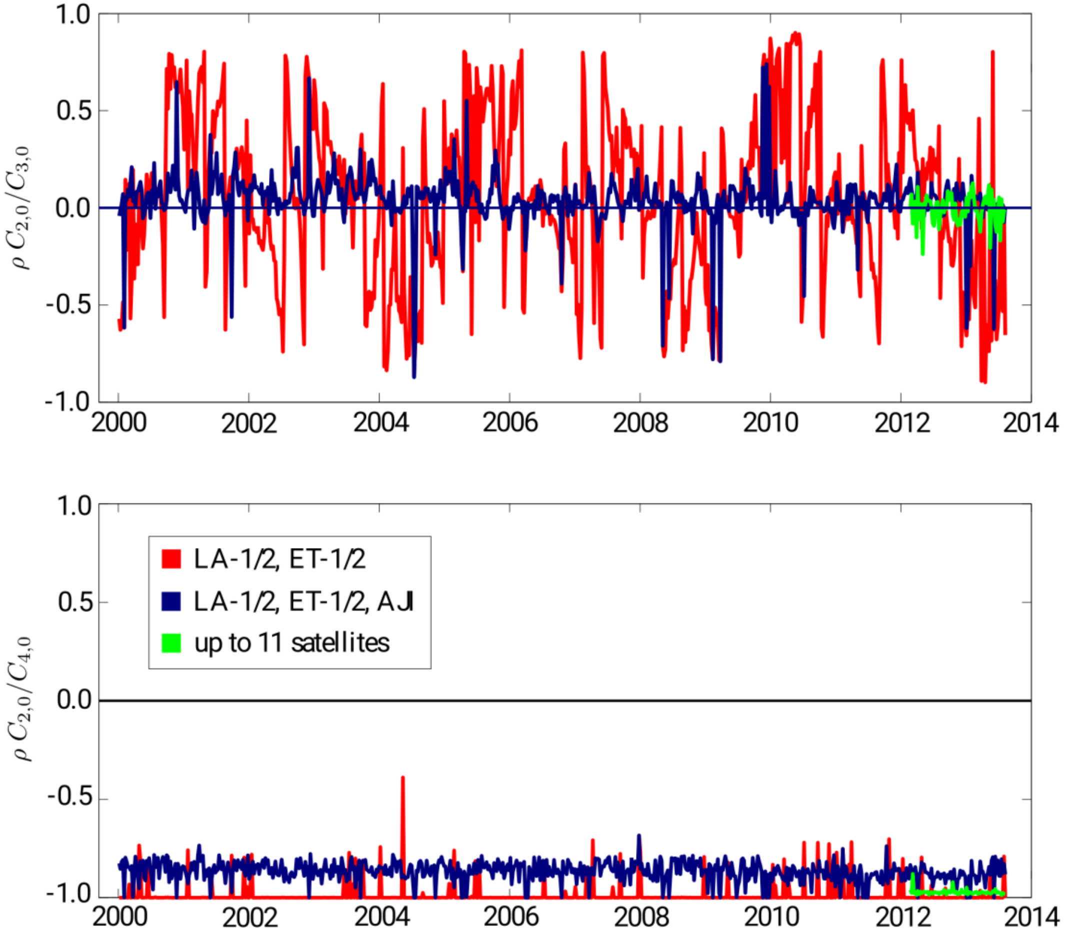
- With an increased number of used satellites, the solution gains sensitivity w.r.t. the Earth's gravity field.
- 4 satellites: up to d/o 3
- 5 satellites: up to d/o 6 (higher d/o for tesseral coefficients)
- Max. constellation: up to d/o 12

But:

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



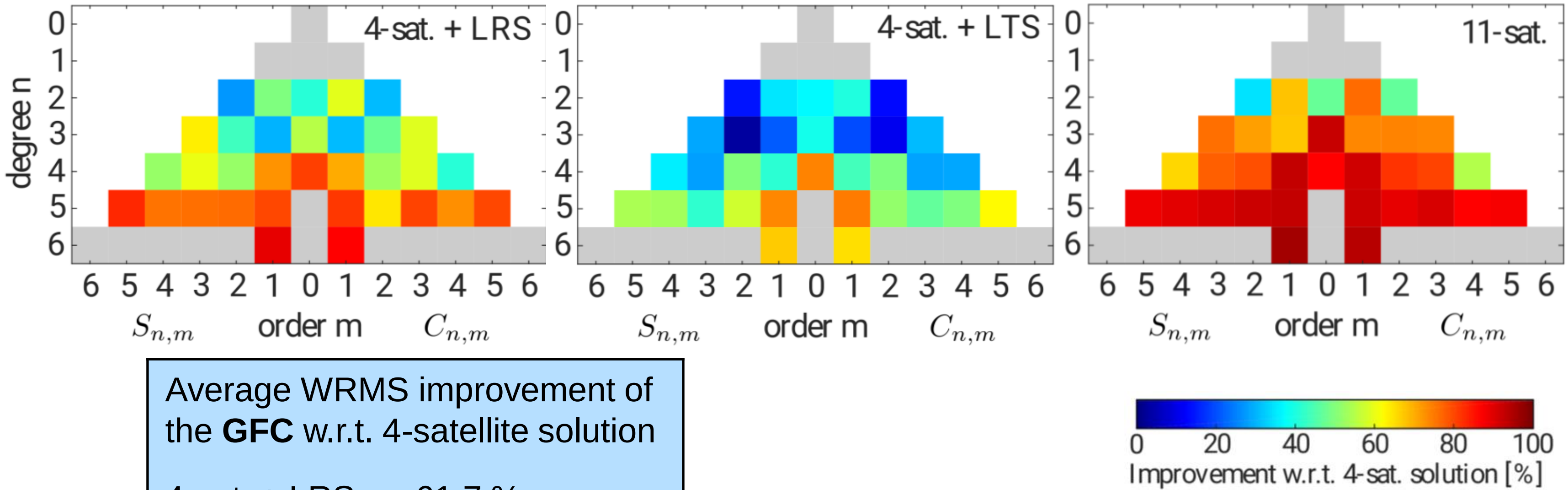
Correlations between gravity field coefficients



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

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

Results: Improvement of gravity field coefficients

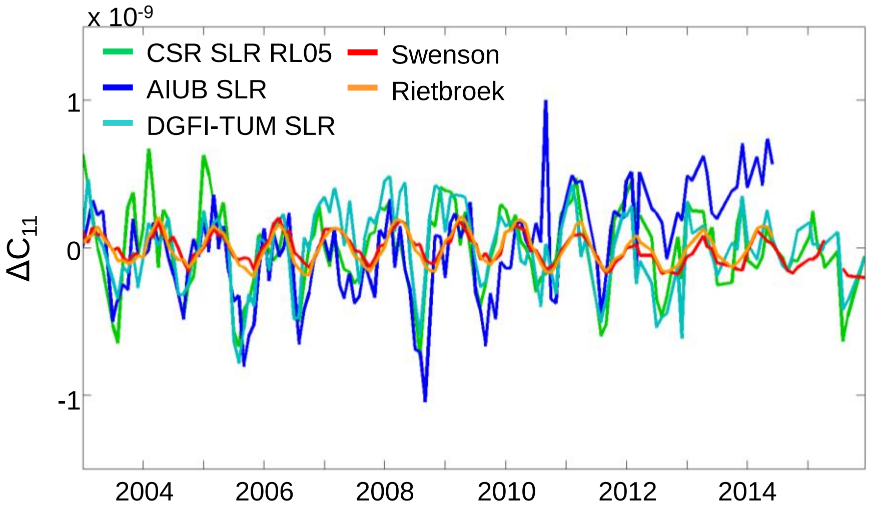


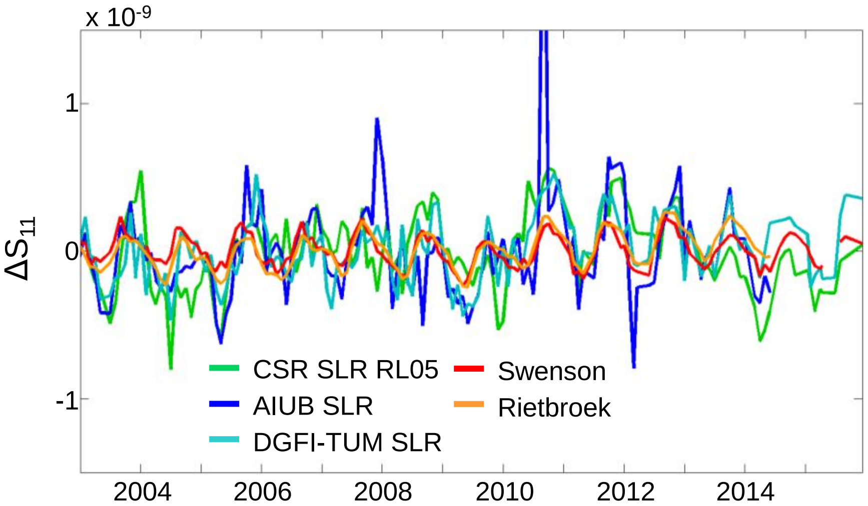
Average WRMS improvement of the **GFC** w.r.t. 4-satellite solution	
4-sat. + LRS	61.7 %
4-sat.+ LTS	41.9 %
11-sat.	79.3 %

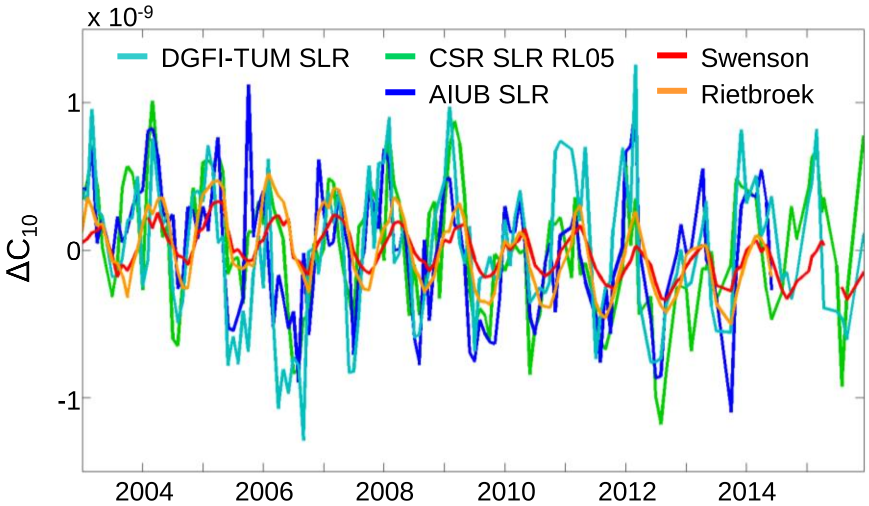
Improvement of the mean WRMS values w.r.t. 4-satellite solution

- 5-satellite solution: different improvement patterns depending on the orbit of the additional satellite
- 11-satellite solution: improvement by up to 93 %

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

Summary and Outlook

- The inclusion of additional satellites at various altitudes and orbit inclinations into the SLR solutions reduces correlations between the estimated parameters and increases the sensitivity of the solution to higher degree GFC.

- An 11-satellite setup allows for a reliable estimation of all parameters in a common adjustment.

- TRF datum parameters are improved by up to 35 %, station repeatability - by up to 22 %
- EOP are improved by up to 22 %
- GFC are improved by up to 94 %

- As the 5-satellite setup including LARES performs well, these results support the plan to include this satellite into the ILRS standard setup.

- The DGFI-TUM solution of the geocenter motion derived from 11-satellite SLR constellation is comparable to other geocenter motion solutions derived from SLR data.

A publication to the subject:
Bloßfeld et al.: ***"Consistent estimation of geodetic parameters from SLR satellite constellation measurements", s***ubmitted to "Journal of Geodesy" (in review)

Backup slides

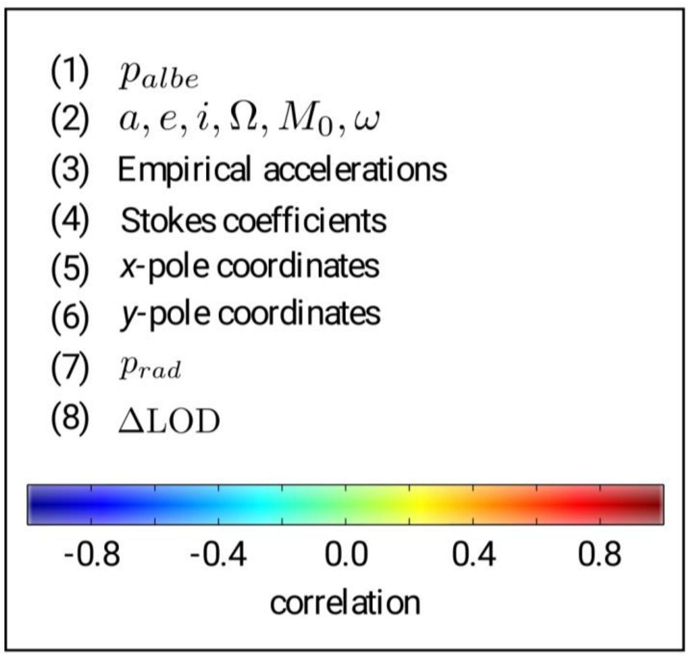
Summary

+ Improvement

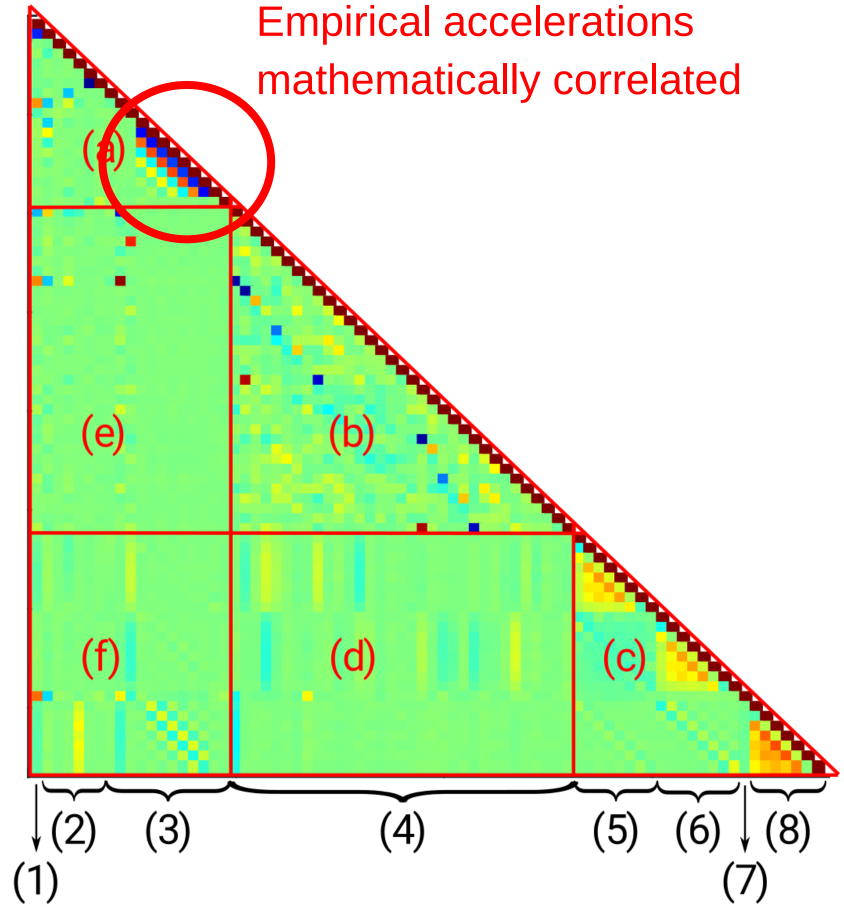
– Degradation

		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

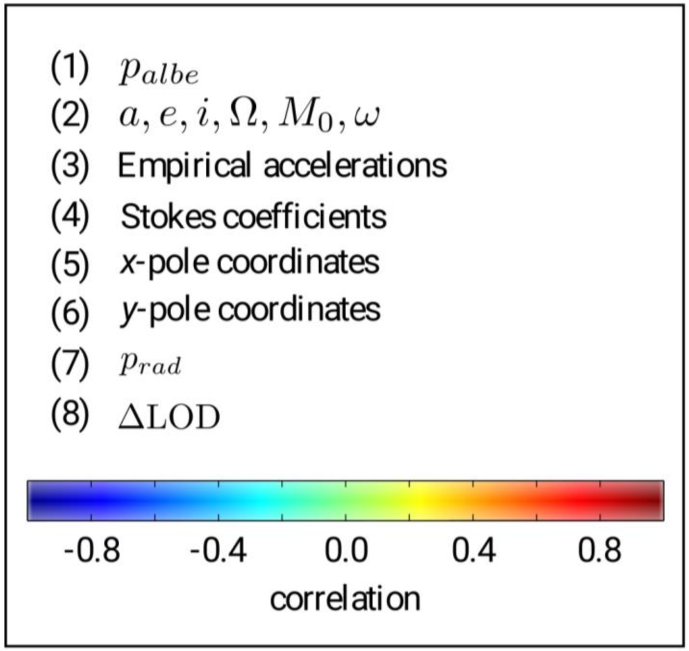
Correlations between parameters

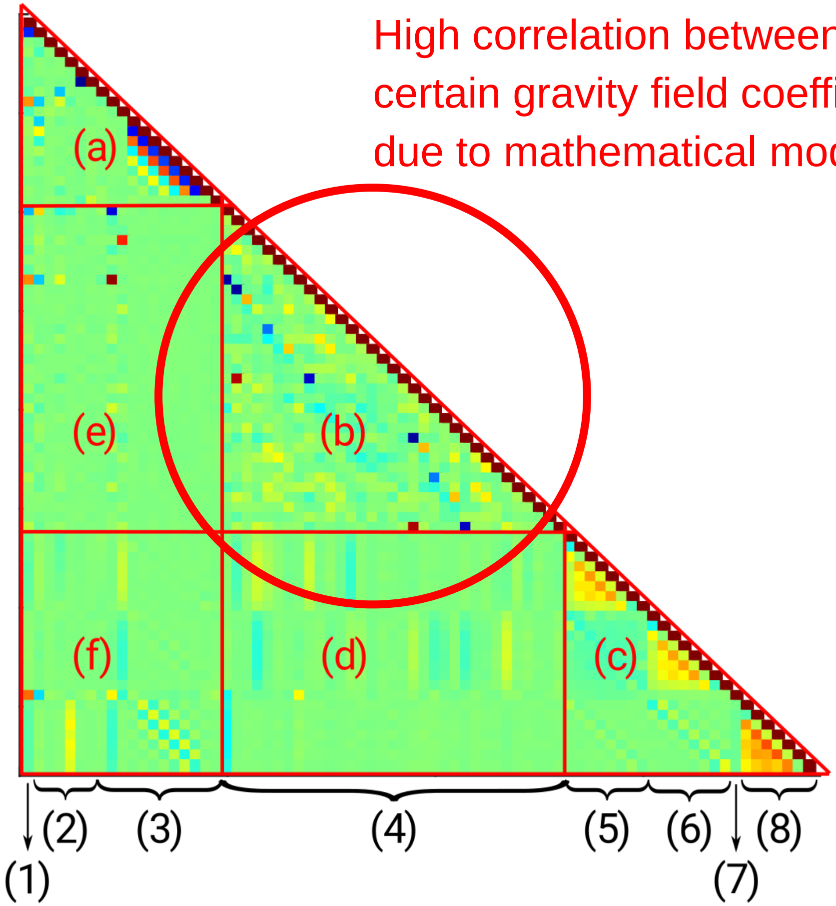


Empirical accelerations mathematically correlated



Correlations between parameters





Correlations between parameters