Contribution of consistent laser observations to Earth system sciences

Mathis Bloßfeld
with contributions of A. Kehm and H. Müller

Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)
Technische Universität München

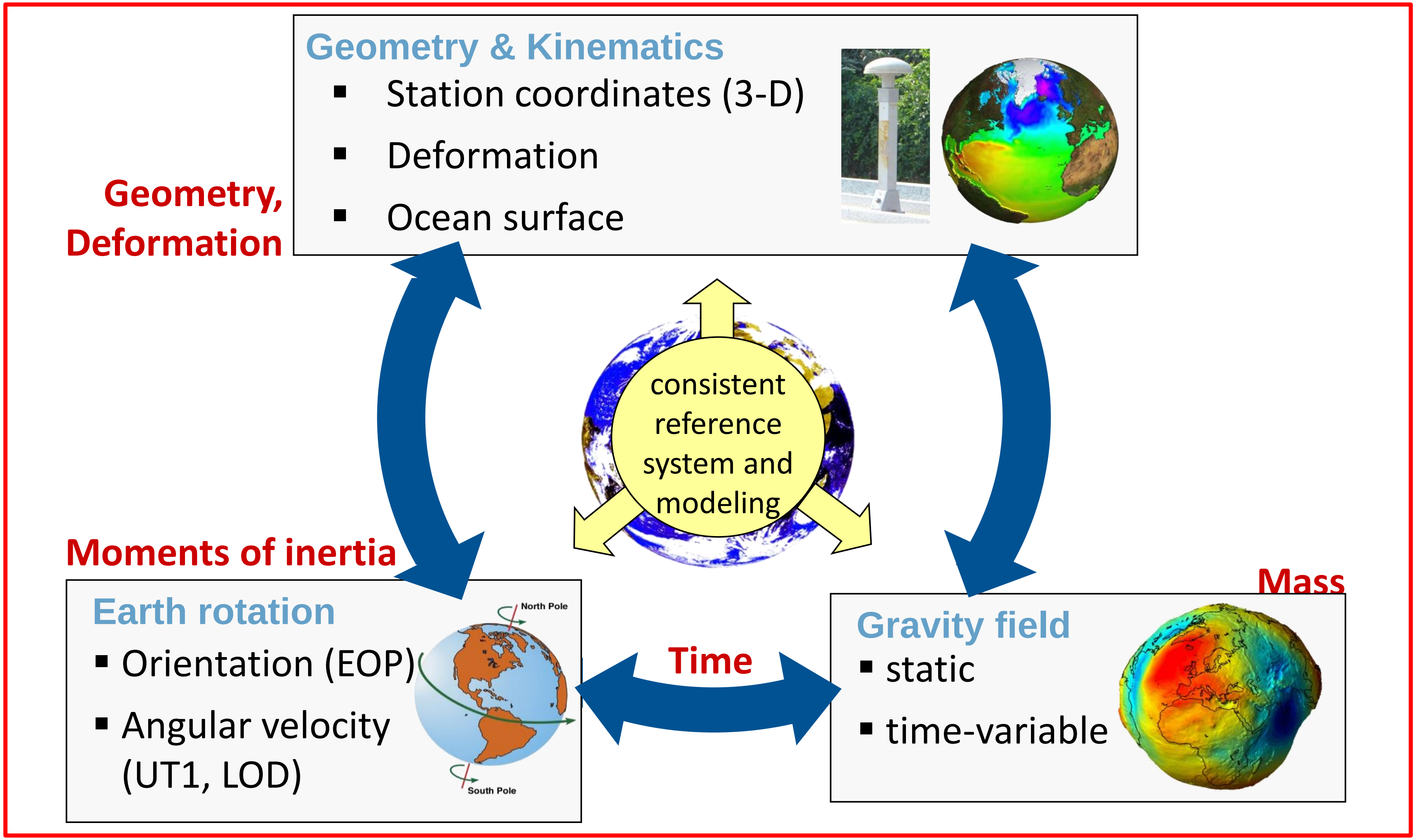
20th International Workshop on Laser Ranging,
Potsdam, Germany, 10.10.2016

Earth System Sciences

- In the past, geodesy was the discipline of measuring separately the shape, rotation and gravitational field of the Earth
- Nowadays, geodesy
  - has turned into a multi-disciplinary science
  - provides reliable and accurate measurements of a highly dynamic and complex system Earth
  - includes the interpretation of the observed changes
  - benefits from the multitude of diverse sensor systems

- The integration of the different sensor systems into one global observing system allows to fully exploit their individual strengths

Global Geodetic Observing System (GGOS)



Geometry & Kinematics

- Station coordinates (3-D)
- Deformation
- Ocean surface

Geometry, Deformation

consistent reference system and modeling

Moments of inertia

Earth rotation

- Orientation (EOP)
- Angular velocity (UT1, LOD)

Time

Mass

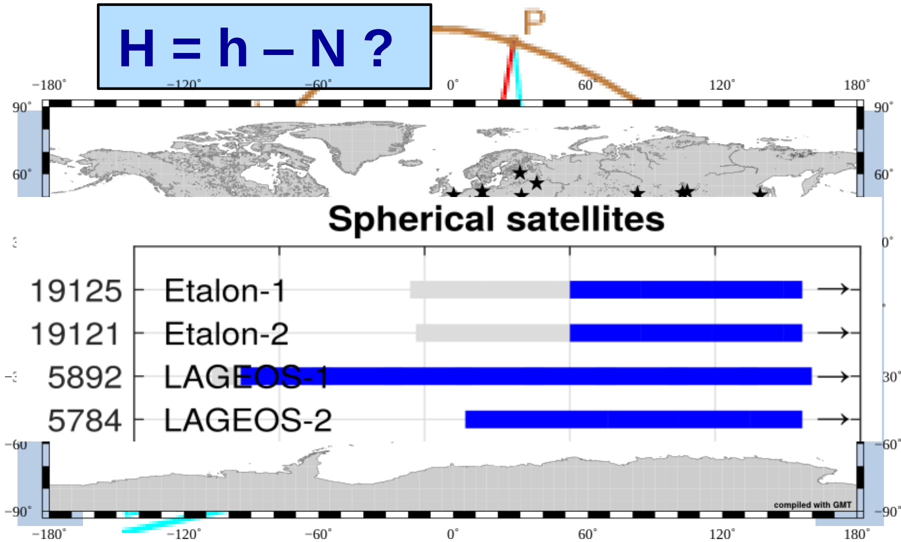
Gravity field

- static
- time-variable

highly accurate terrestrial/celestial reference systems and satellite orbits

Satellite Laser Ranging (SLR)

- ☐ SLR is capable to determine a broad variety of geodetic parameters with high accuracy, since it is
  - **sensitive w.r.t. the reference frames (ITRF/satellite orbits) and the EOP:** measurement principle: 2-way light travel time measurements from crust-fixed stations to satellites in the inertial frame
  - **sensitive to the long wavelengths of the Earth's gravity field (Stokes coefficients):** measured orbit disturbances of spherical satellites
  - Problems:
    - ➢ **Non-common standards**
    - ➢ **non-homogeneous ground-based infrastructures**
    - ➢ **high correlations between parameter groups**
    - ➢ **unused observations**



SLR within GGOS

Integration by GGOS

Integration by GGOS

IERS/ IGFS	Target parameters	SLR	LLR	GNSS	VLBI	DORIS	Altimetry	CHAMP, GRACE, GOCE, …
ICRF	Quasar coordinates				X			
	Satellite orbit parameters	X		X		X	X	
	Lunar orbit parameters		X					
EOP	Nutation		X	(X)	X	(X)		
	Polar motion	X	X	X	X	X		X
	UT1-UTC			(X)	X	(X)		
	Length of day	X	X	X	X	X		X
ITRF	Station coordinates / velocities	X	X	X	X	X	(X)	X
Gravity field, phys. heights	Scale, Center of Mass / Stokes coefficients of deg. 2	X					(X)	X
	Earth’s gravity field (Stokes coefficients with deg. > 2)	X	(X)	(X)		(X)	X	X
	Sea level						X	
Atm.	Thermosphere			X	X	X	X	X
	Ionosphere			X	X	X	X	X

current ILRS products

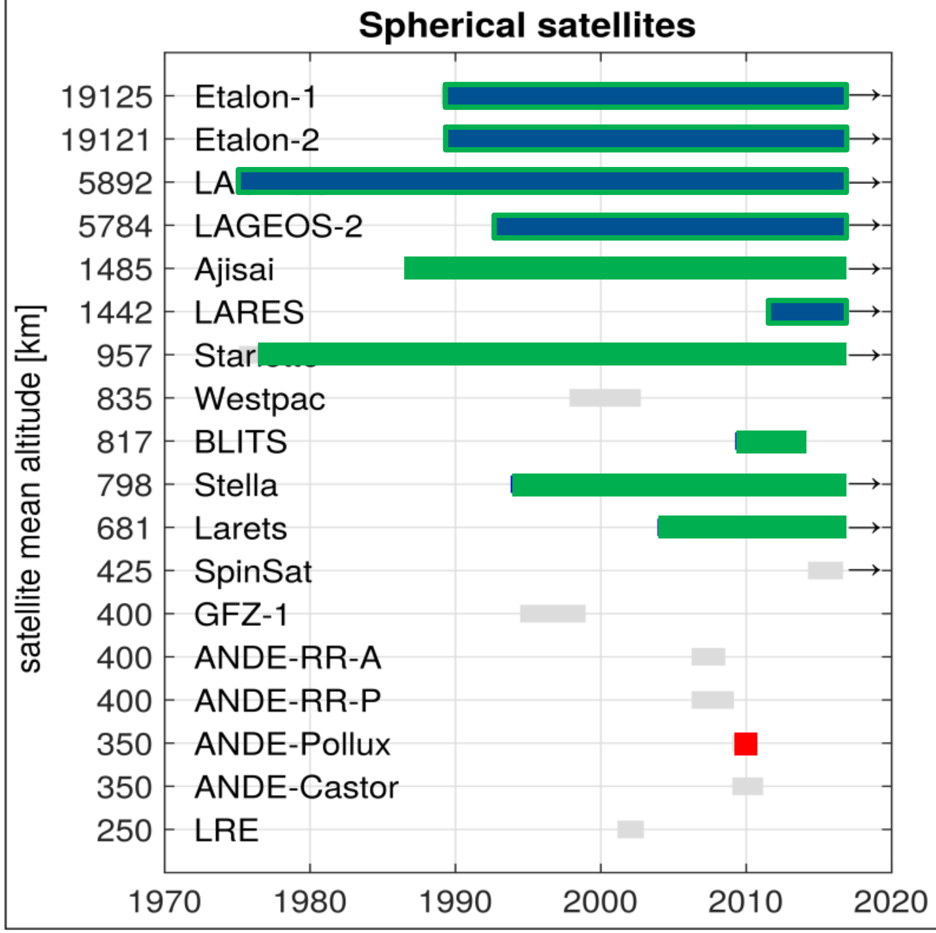
future ILRS products

Motivation for whole ILRS community

- ☐ In the last decades, the ILRS community achieved significant improvements in terms of
  - measurement accuracy,
  - global SLR station network evolution,
  - analysis quality.
- ☐ In this talk, selected developments are emphasized which are/will be possible due to the community efforts:
  - **already possible**: new parameters determined through highly accurate SLR measurements
  - **already possible**: estimation of integrated TRF, EOP and gravity field solutions using laser observations to satellite constellations
  - **in future**: increase of accuracy due to "better" station performances and SLR network evolution

ILRS geodetic space segment (no GNSS, …)

- ☐ **current/future ILRS products**, **thermosphere**, **TRF+EOP+Gravity**



Estimation of integrated thermospheric density variations using SLR

Estimating thermospheric density variations with SLR

- Equation of motion of near-Earth satellites

Direct Gravitational acceleration

Indirect Gravitational acceleration

Non-Gravitational acceleration

$$\ddot{\boldsymbol{r}}_{\mathrm{sat}}(t) = \underbrace{\boldsymbol{a}_{\mathrm{KEP}}(t) + \boldsymbol{a}_{\mathrm{GE}}(t) + \boldsymbol{a}_{\mathrm{GM}}(t) + \boldsymbol{a}_{\mathrm{GS}}(t)}_{\boldsymbol{a}_{\mathrm{DG}}(t)} + \underbrace{\boldsymbol{a}_{\mathrm{GT}}(t) + \boldsymbol{a}_{\mathrm{GNT}}(t)}_{\boldsymbol{a}_{\mathrm{IG}}(t)} + \boldsymbol{a}_{\mathrm{NG}}(t)$$

- the **non-gravitational acceleration $\boldsymbol{a}_{\mathrm{NG}}$** can be split into:
  - **radiation parts** (direct solar rad. pressure, Earth albedo, satellite eclipses, Poynting-Robertson, Yarkovski-Rubincam (anisotropic thermal radiation), Yarkovski-Schach (infrared radiation)),
  - **drag-like parts** (**atmospheric drag**, solar wind, interplanetary dust),
  - **other parts** (e.g., Earth magnetic field, relativistic effect).
- For (spherical) LEO satellites the **atmospheric drag perturbing acceleration $\boldsymbol{a}_D$** is the **largest one** and, thus, the **main error source** in LEO satellite POD.

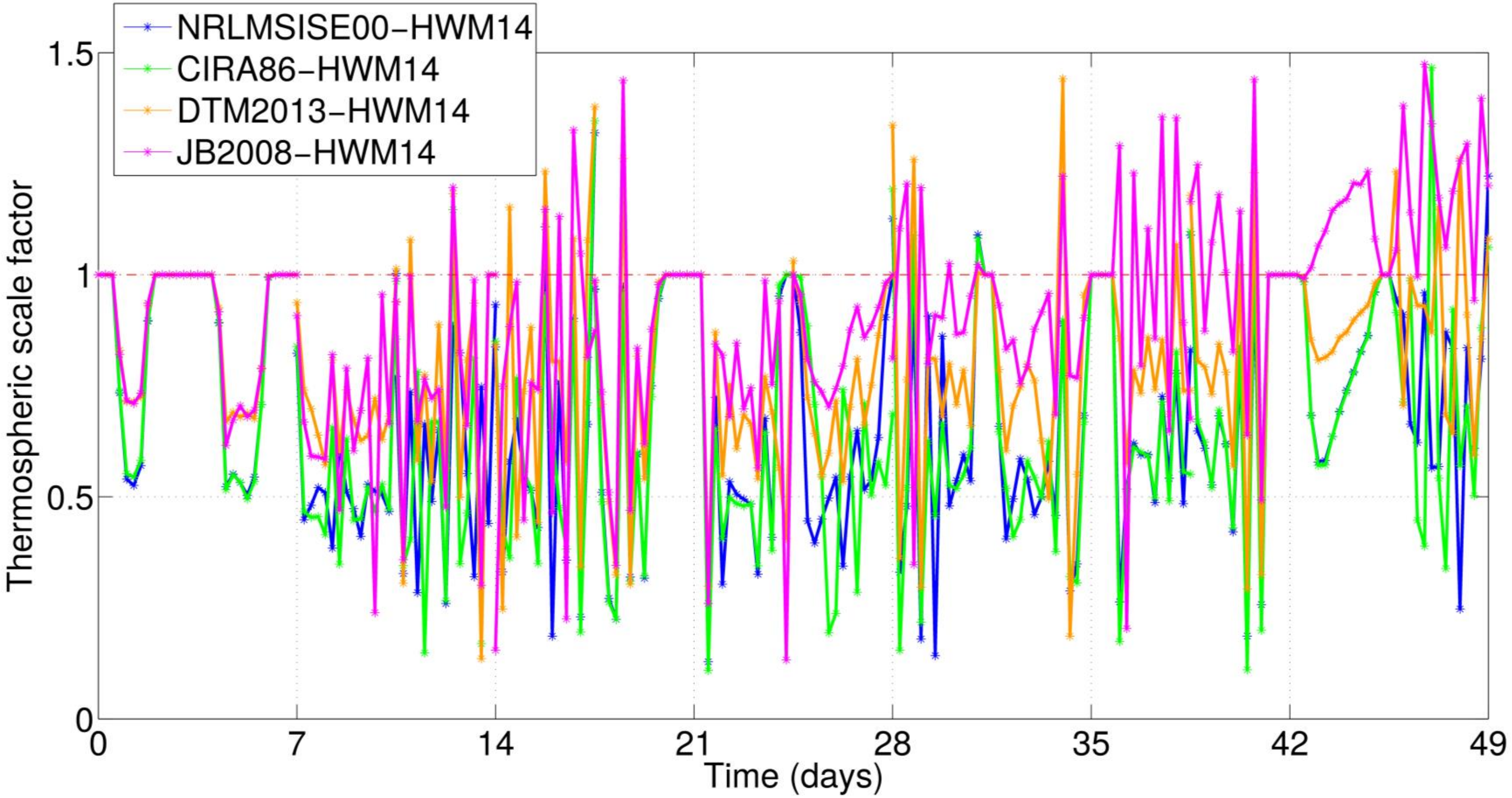
Estimating thermospheric density variations with SLR

❑ ANDE-P → spherical satellite → only drag forces (no side/lift forces)

$$\boldsymbol{a}_D = -\frac{1}{2} \cdot \boldsymbol{f}_{\boldsymbol{s}} \cdot \frac{A_{eff}}{m} C_D \, \rho \, v_{rel}^2 \, \hat{\boldsymbol{u}}_D$$

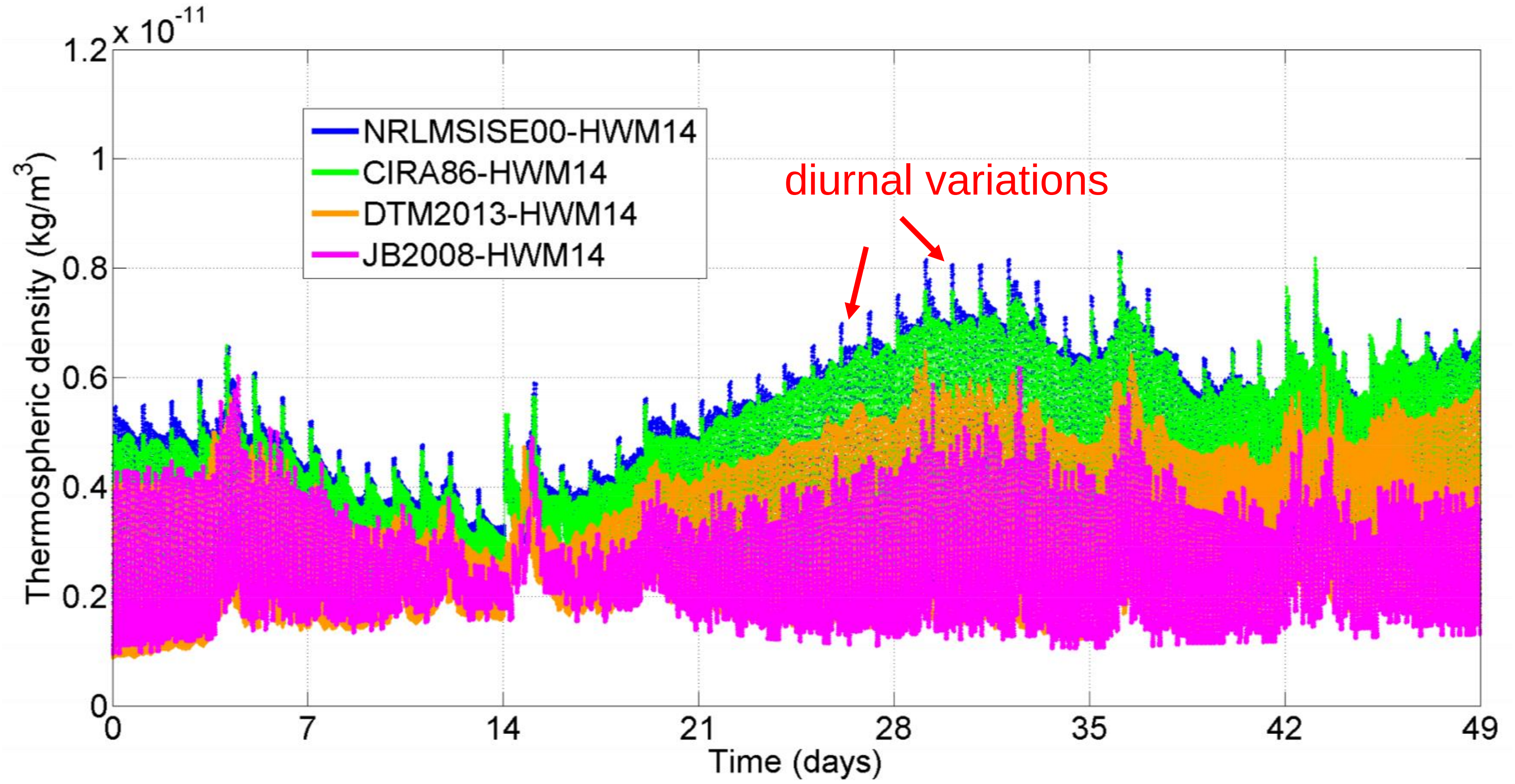
$\hat{\boldsymbol{u}}_D = \frac{\boldsymbol{v}_{rel}}{\lVert \boldsymbol{v}_{rel} \rVert}$	drag unit vector
$\boldsymbol{v}_{rel}$	relative velocity of the satellite w.r.t. the thermosphere
C_D	thermospheric drag coefficient, describing the interaction of the atmosphere with the satellite surface
ρ	integrated thermospheric (neutral) density
A_{eff}	effective satellite cross-section area interacting with the atmosphere
m	satellite mass
$\boldsymbol{f}_{\boldsymbol{s}}$	Lagrange scaling factor → this parameter is estimated (every 6h)!

Estimated Lagrange scaling coefficients f_s



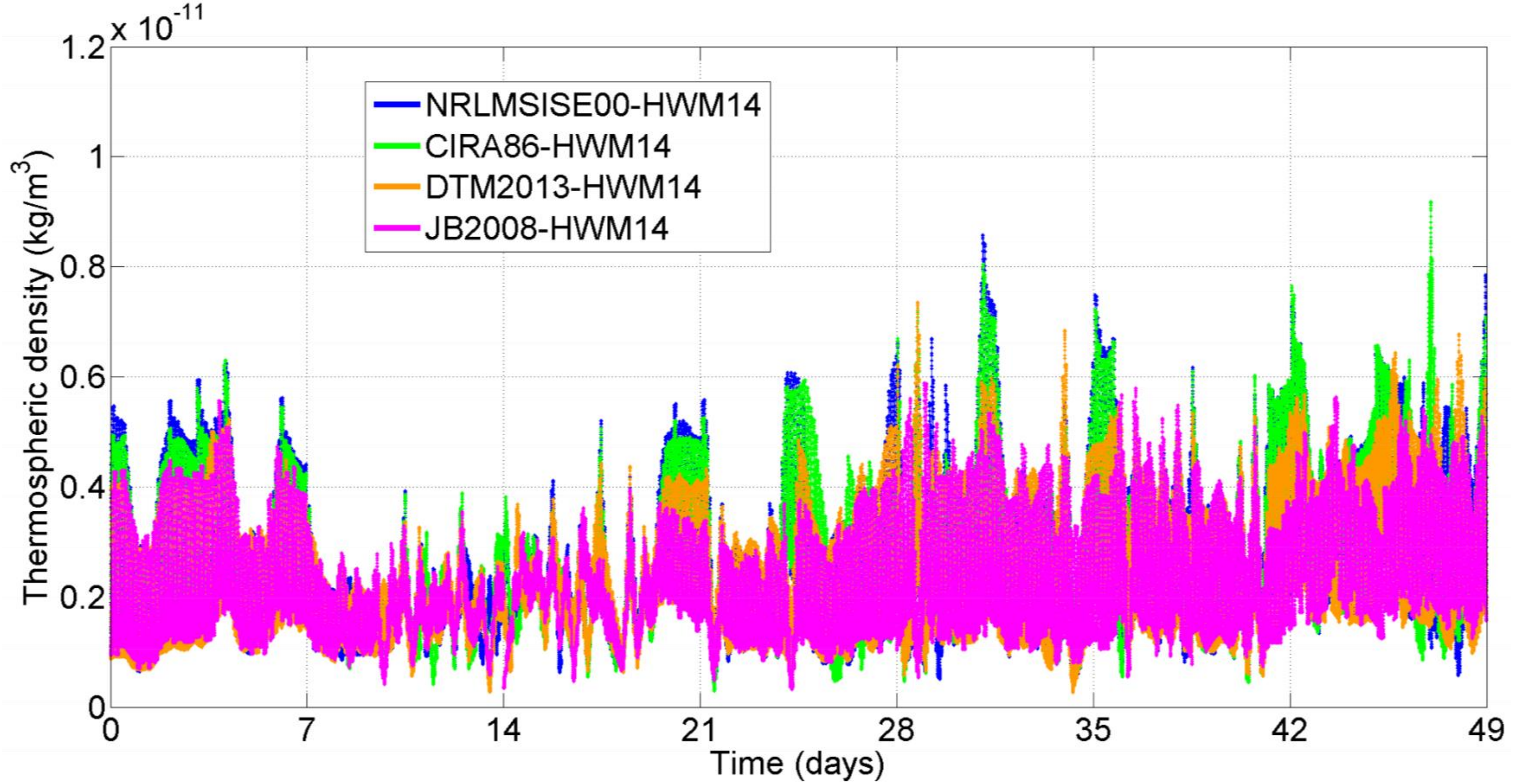
- ➢ If the scaling coefficient is equal to 1 no SLR observations were available
- ➢ NRLMSISE00 and CIRA86 agree very well; more recent models show offset (especially at the end of the time series)

Modeled thermospheric densities *ρ*



- JB2008 shows in general the lowest density distribution values
- Large offset of JB2008 w.r.t. CIRA86 and NRLMSISE00; smaller offset w.r.t DTM2013

Scaled thermospheric densities $f_s \cdot \rho$

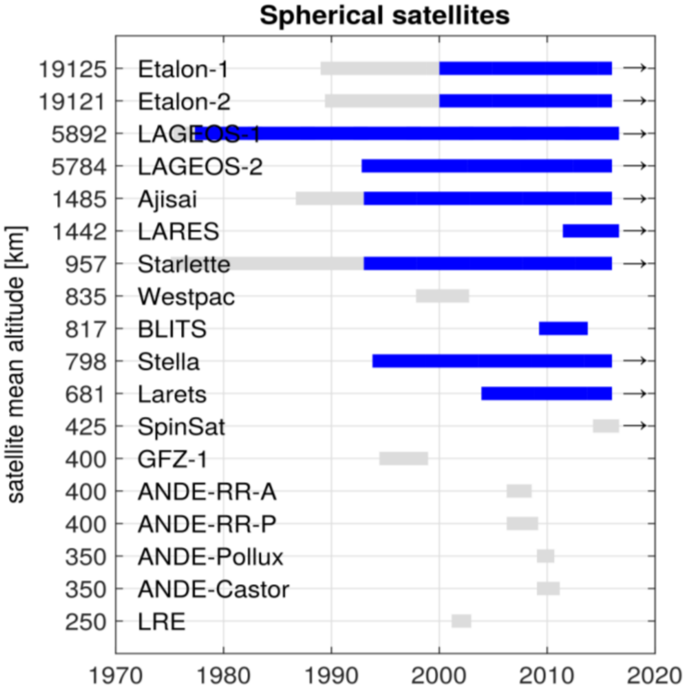


- In general, CIRA86 and NRLMSISE00 are scaled to more recent models
- No offset change for JB2008 and DTM2013
- Density variations of JB2008 and DTM2013 are reduced

De-correlation of gravitational field parameters using SLR constellation observations

SLR de-correlation and sensitivity tests (I)

- ☐ In order to obtain reliable estimates of the Stokes coefficients, it is essential to de-correlate the orbital parameters and the coefficients of the Earth‘s gravitational field.
  - **Test 1**: De-correlation of orbit parameters and C_{20} (table taken from Bloßfeld et al., 2015)



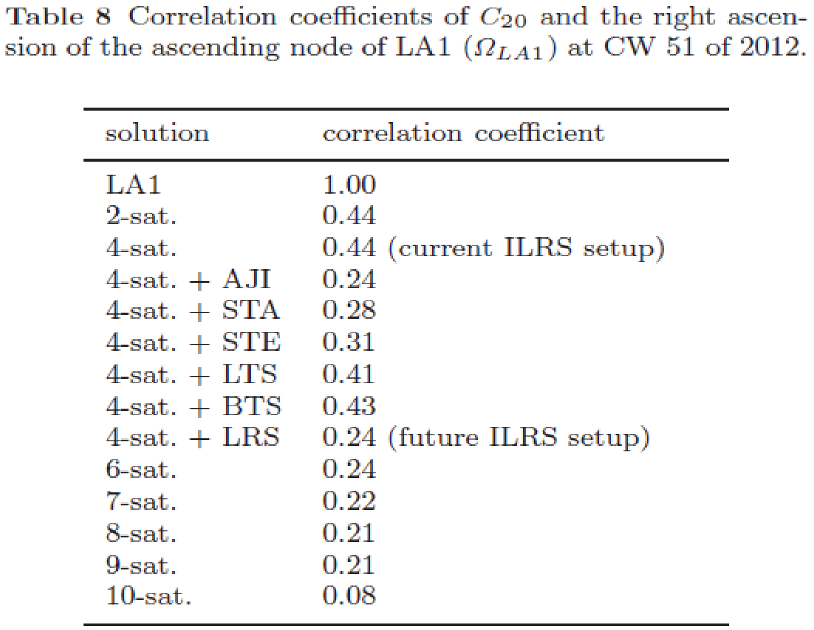
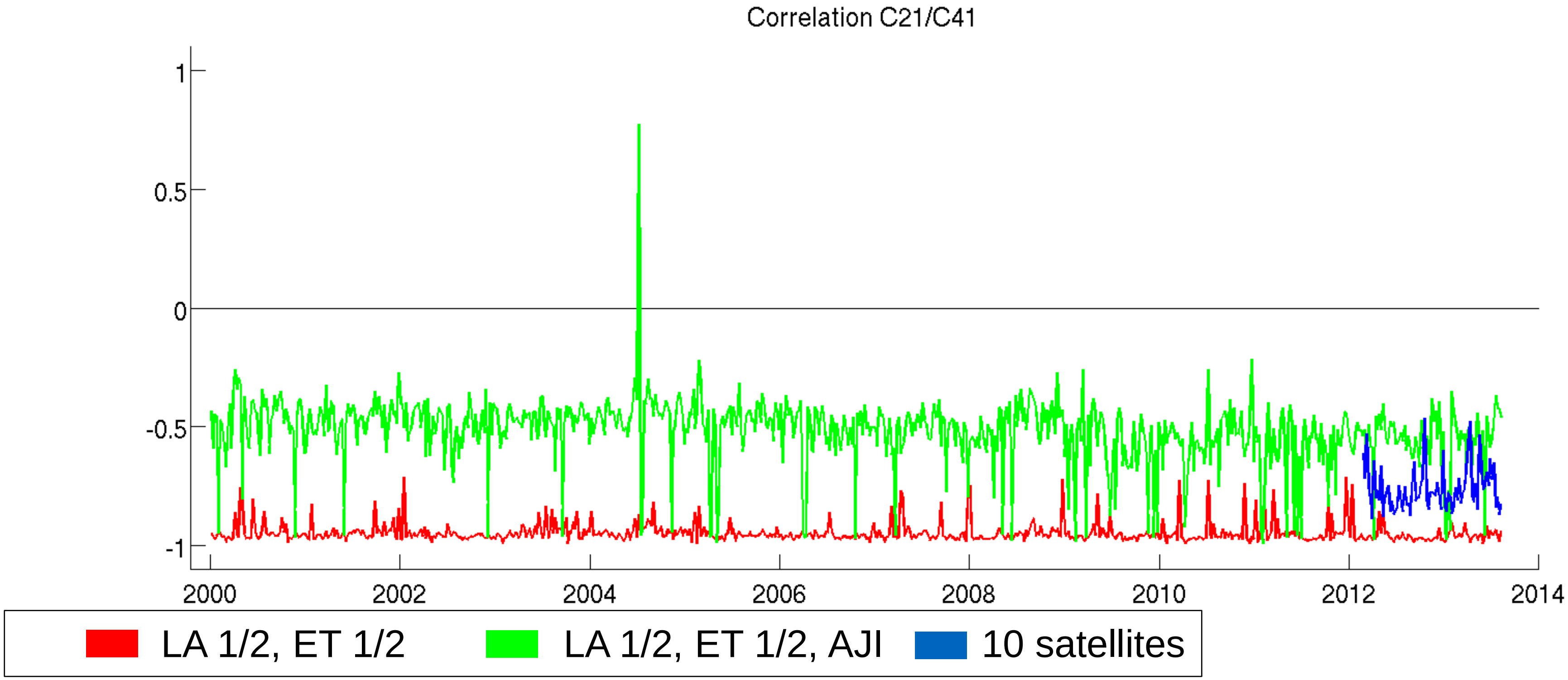


Table 8 Correlation coefficients of C_{20} and the right ascension of the ascending node of LA1 (Ω_{LA1}) at CW 51 of 2012.

solution	correlation coefficient
LA1	1.00
2-sat.	0.44
4-sat.	0.44 (current ILRS setup)
4-sat. + AJI	0.24
4-sat. + STA	0.28
4-sat. + STE	0.31
4-sat. + LTS	0.41
4-sat. + BTS	0.43
4-sat. + LRS	0.24 (future ILRS setup)
6-sat.	0.24
7-sat.	0.22
8-sat.	0.21
9-sat.	0.21
10-sat.	0.08

SLR de-correlation and sensitivity tests (II)

- ☐ In order to obtain reliable estimates of the Stokes coefficients, it is essential to de-correlate the orbital parameters and the coefficients of the Earth‘s gravitational field.
  - ➢ **Test 2**: De-correlation of Stokes coefficients using multi-satellite SLR solution



SLR de-correlation and sensitivity tests (III)

☐ In order to obtain reliable estimates of the Stokes coefficients, it is essential to de-correlate the orbital parameters and the coefficients of the Earth‘s gravitational field.

- **Test 3**: Sensitivity analysis w.r.t. Stokes coefficients
- This test is based on the PhD thesis of R. Floberghagen (2002);

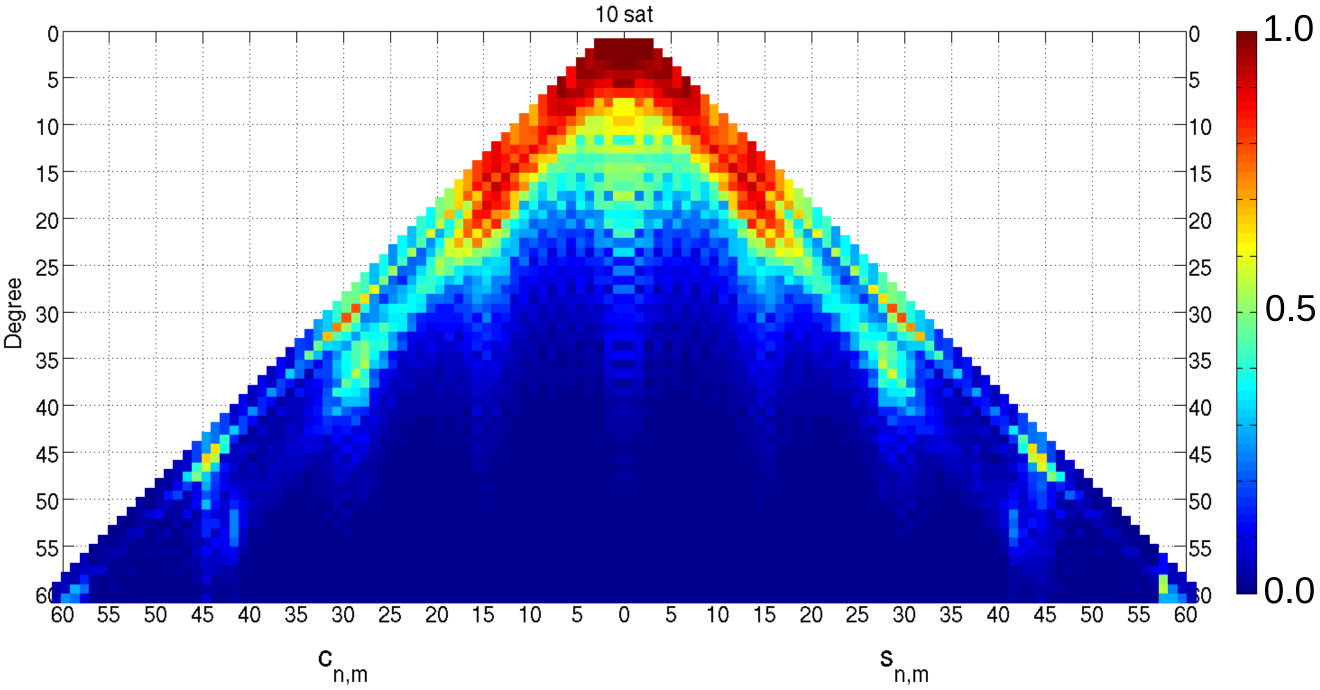
$$[0;1]\,\epsilon\,diag(N^{-1}N) = (A^TPA + \alpha K)^{-1}(A^TPA)$$

- **Important:** sensitivity coefficient equal to one means that the Stokes coefficient is fully determinable from the observations
- **BUT:** some coefficients are highly correlated (Haberkorn et al., 2014) and therefore only a linear combination of them (Kaula, 1966) can be estimated (e.g., even zonal low degree Stokes coefficients)

SLR de-correlation and sensitivity tests (IV)

- ☐ In order to obtain reliable estimates of the Stokes coefficients, it is essential to de-correlate the orbital parameters and the coefficients of the Earth‘s gravitational field.
  - ➢ **Test 3**: Sensitivity analysis w.r.t. Stokes coefficients (e.g. Jan 2012)

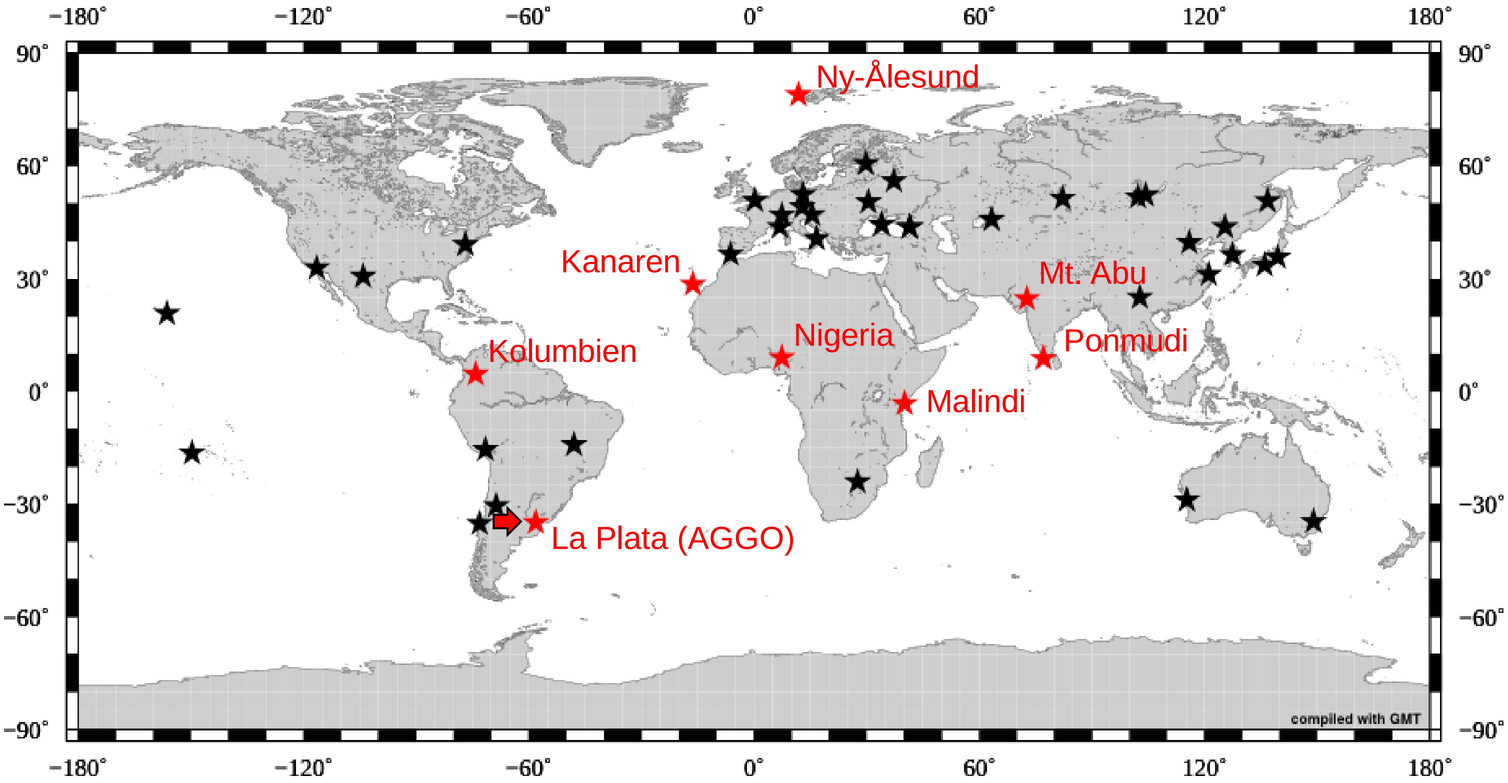
LA 1/2
+ ET 1/2
+ AJI
+ STA
+ STE
+ LTS
+ BTS
+ LRS
+ JA2



ILRS station performance and geodetic network evolution

Ground-based infrastructures

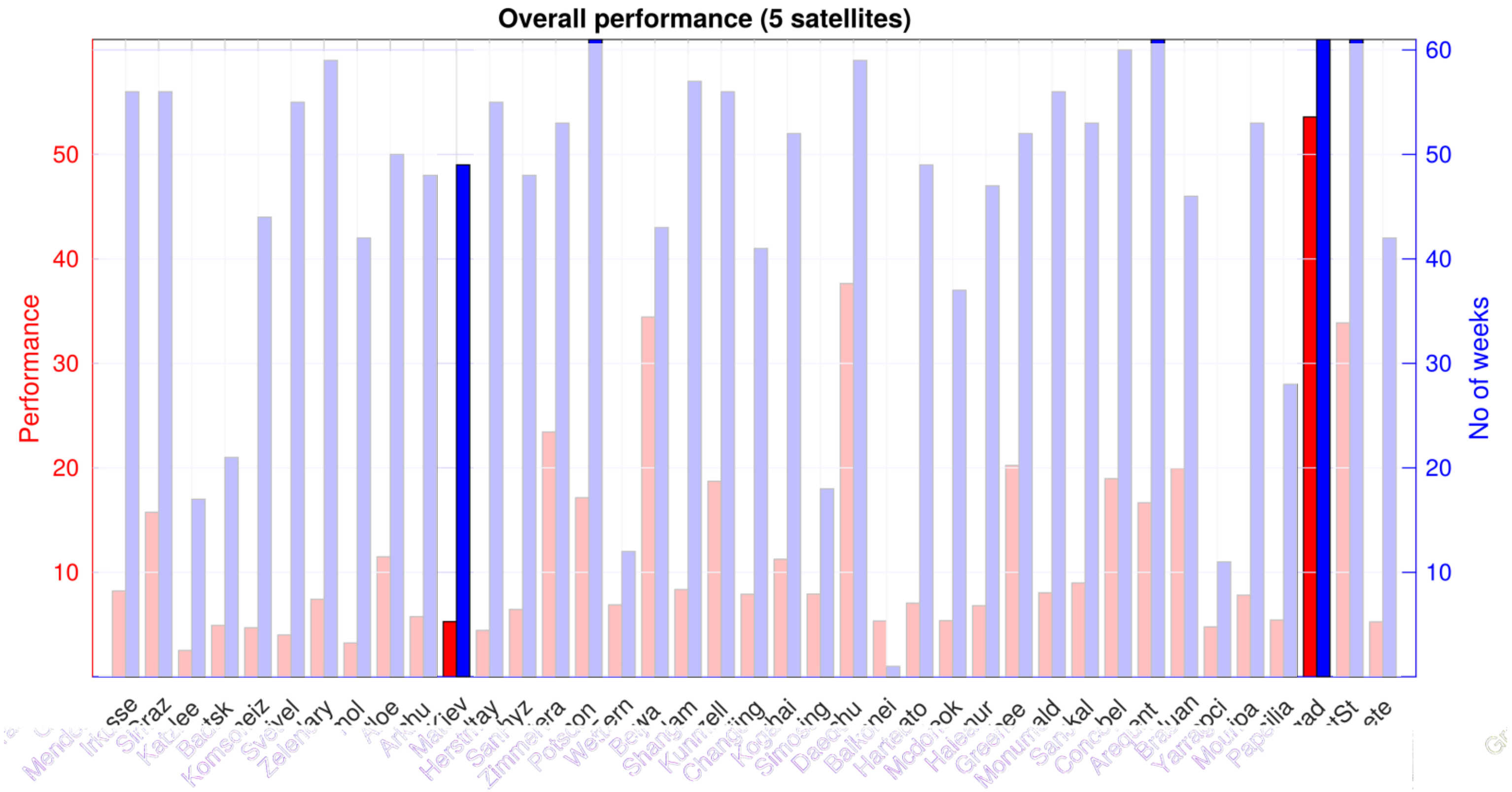
☐ Can geodetic parameters be improved by a more homogeneously distributed ground station network?



➢ Simulation of 8 planned/nearly operational stations (acc. to ILRS GB minutes)

Ground-based infrastructures

- ☐ Can geodetic parameters be improved by a “better” station performance (station upgrade)?



performance = $\frac{\text{number of possible passes}}{\text{number of observed passes}}$ (mean: 13%)

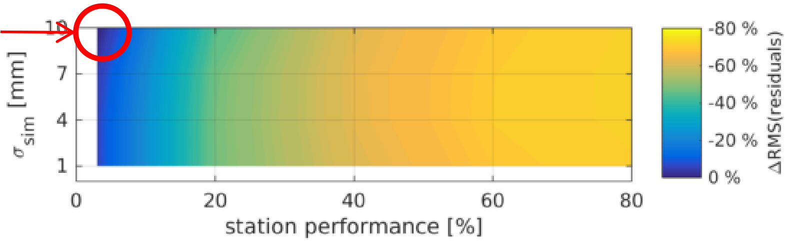
time period: 12/2013 – 02/2015 (61 weeks)

Ground-based infrastructures

- Improvement of weekly transformation RMS (lower scatter w.r.t. SLRF2008)

real station network (impact of station upgrade)

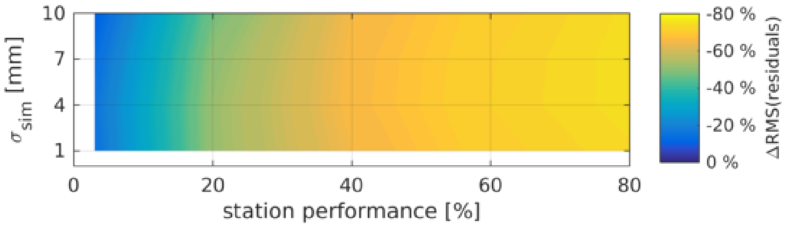
reference solution
$\sigma_{\text{sim}} = 10\ \text{mm}$
real performances



0 % … 72,8 %

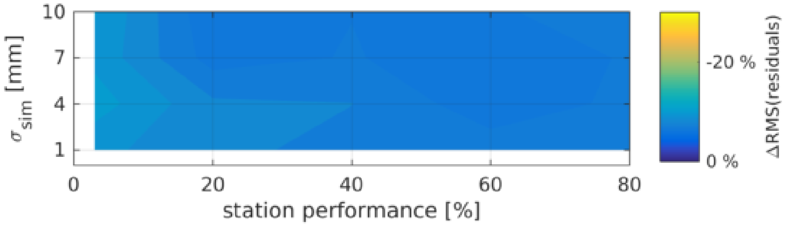
Improvement w.r.t. reference solution

extended station network (station upgrade + improved network geometry)



10,1 % … 74,7 %

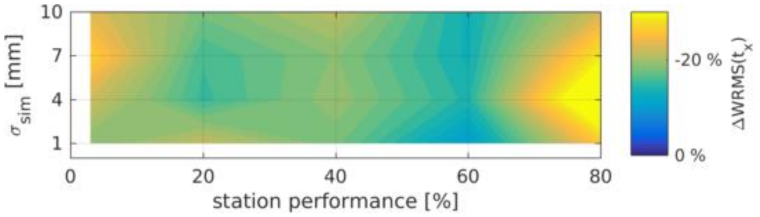
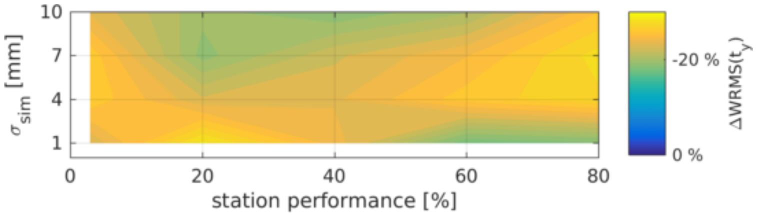
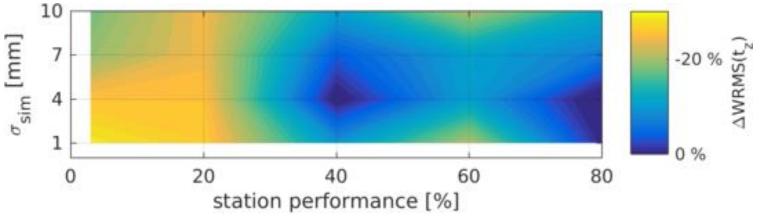
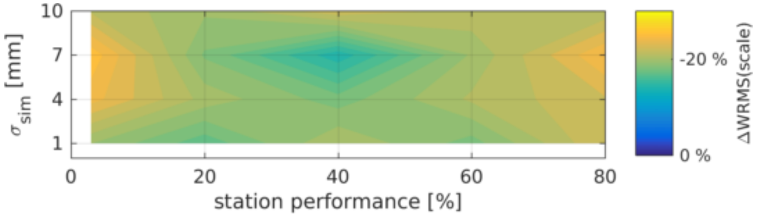
Improved network geometry



10,0 % ± 1,3 %

Ground-based infrastructures

☐ Improvement of physical datum parameters due to network geometry

t_x	 **20.6 % ± 6,2 %**
t_y	 **23.7 % ± 3,4 %**
t_z	 **15.1 % ± 9,9 %**
M	 **20.7 % ± 7,7 %**

Ground-based infrastructures

- ❑ **“Better” station performances** improve the geodetic parameters significantly
- ❑ Significant improvement of x- and z-translation due to **improved network geometry**
- ❑ Assumption: mean improvement of all station performances at least to 20%:

	physical geodetic datum parameters					EOP		
	RMS	t_x	t_y	t_z	scale	x_{Pol}	y_{Pol}	LoD
perf.	44 %	10 %	27 %	14 %	49 %	10 %	10 %	4 %
geom.	6 %	18 %	20 %	24 %	20 %	4 %	5 %	2 %
comb.	48 %	26 %	41 %	35 %	59 %	13 %	15 %	6 %

- ❑ Be aware:
  - ➢ impact discussed here: SLR-only network → larger impact if co-locations with other techniques are improved
  - ➢ impact on satellite POD/gravity field determination might be larger since geographical gaps are filled

Conclusions

- ☐ SLR is the key observing technique to achieve the GGOS goals
- ☐ Currently, the potential of SLR measurements is not yet fully exploited
  - ➢ the ILRS operational products contain „only“ observations to 4 (5) geodetic satellites (13 might be used)
  - ➢ no gravitational field coefficients are estimated (BUT: ILRS pilot project already running)
- ☐ New parameters such as integrated thermospheric density estimations can be estimated due to the high quality of SLR measurements to LEOs
- ☐ A consistent estimation of TRF, EOP and gravity field is only possible if laser observations to satellite constellations are used
- ☐ Station upgrades are as important as new stations (improvements up to 60% are possible for ITRF origin and scale)

Contribution of consistent laser observations to Earth system sciences

Mathis Bloßfeld
with contributions of A. Kehm, H. Müller

Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)
Technische Universität München

20th International Workshop on Laser Ranging,
Potsdam, Germany, 10.10.2016