Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters

- status report PN 6 -

Mathis Bloßfeld, Natasha Panafidina, Manuela Seitz
with contributions of Francesca Panzetta and Alexander Kehm

Deutsches Geodätisches Forschungsinstitut (DGFI-TUM),
Technische Universität München

Project meeting of DFG Research Unit “Space-time Reference Systems for Monitoring Global Change and for Precise Navigation in Space“
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DFG Forschergruppe Referenzsysteme

Future plans of last status seminar

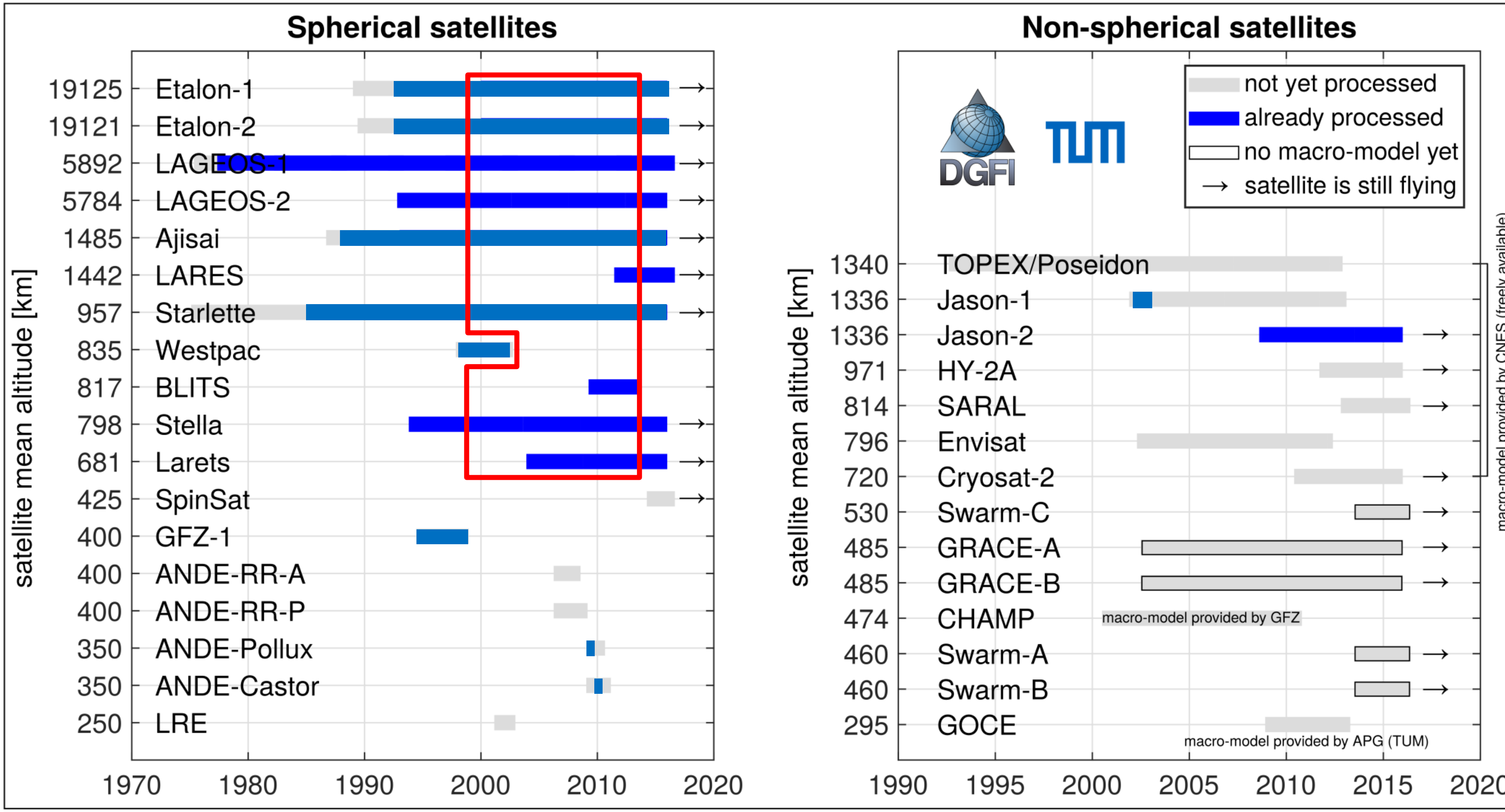
- Include further LEO satellites in the SLR multi-satellite solution for geodetic parameter estimation (spherical and non-spherical) in order to **increase the sensitivity to the gravity field** (2^{nd} degree Stokes coefficients) and to **improve the geophysical datum**
- Enlarge the TRF interval (last meeting: three years)
- Simulate LEO satellites and SLR stations to test their capability to improve the geophysical datum
- Combination of SLR and GNSS at NEQ level
- Refined realization of a physical TRF orientation

➢ What is the current sensitivity of the SLR multi-satellite solution? To what degree and order can the Stokes coefficients be determined (correlations, sensitivity)?

Work packages in 2nd funding phase (DGFI-TUM part)

- **WP 6110**: implementation of Jason-2 and SWARM models into DOGS-OC and SLR observation analysis
  - up to now, macro models of Jason-1/2 have been implemented; SWARM-A/B/C will be available for implementation in August
  - **refined modeling of non-gravitational perturbations** in DOGS-OC
  - complete analysis of SLR observations to Jason-2; Jason-1 was started; SWARM will be started in August
  - **3.5-day Jason-2 NEQs were combined with weekly 10-satellite SLR-NEQs**
- **WP 6210**: simulation of SLR observations
  - new satellites like, e.g., E-GRASP were simulated
  - **planned new SLR stations were simulated**
  - **a minimum (optimum?) observation scheduling has been selected**

SLR multi-satellite solution – current status



Refined modeling of non-gravitational perturbations

- For processing LEO satellites at very low altitudes (250 to 700 km), the modeling of the non-gravitational perturbations (especially due to the thermosphere) had to be refined in DOGS-OC
  - ➢ different **thermospheric models** in order to test sensitivity (currently, CIRA86, NRLMISE-00, JB2008 and DTM2013 are incorporated)
  - ➢ **horizontal wind model** (HWM14 incorporated)
  - ➢ **physically defined drag-/lift-/side-coefficients** $\boldsymbol{c_{D/L/S}}$ (important in order to estimate purely thermospheric density coefficients).

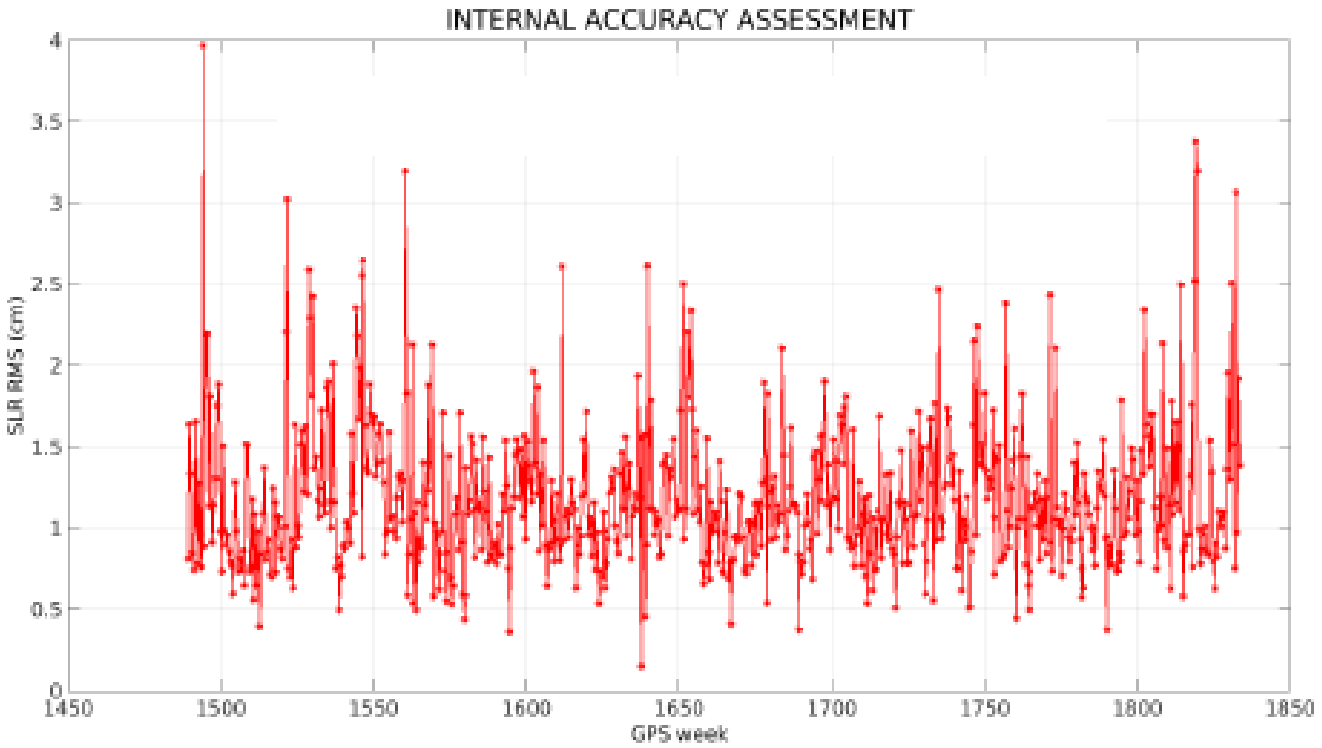
    Critical in the thermospheric modeling due to numerous basic assumptions (e.g., **Gas-Surface-Interaction modeling; GSI-model**) and modeled key parameters (e.g., **satellite surface temperature**)

Refined handling of Jason-2

- Numerous routines of DOGS-OC have been refined in order to be able to process SLR observations to non-spherical satellites
- For example, the implementation of Jason-2 comprised
  - ➢ the Jason-2 macro model (e.g., optical properties of satellite surfaces)
  - ➢ the attitude control (using quaternions and solar panel rotation angles)
  - ➢ the yaw-steering and eclipse model (to bridge quaternion gaps)
  - ➢ the mass history handling (to handle change of satellite CoM)
  - ➢ the Jason-2 LRA phase center
  - ➢ the handling of special (abrupt) maneuvers
- After a time-consuming outlier detection, the analysis of all available SLR observations to Jason-2 was possible

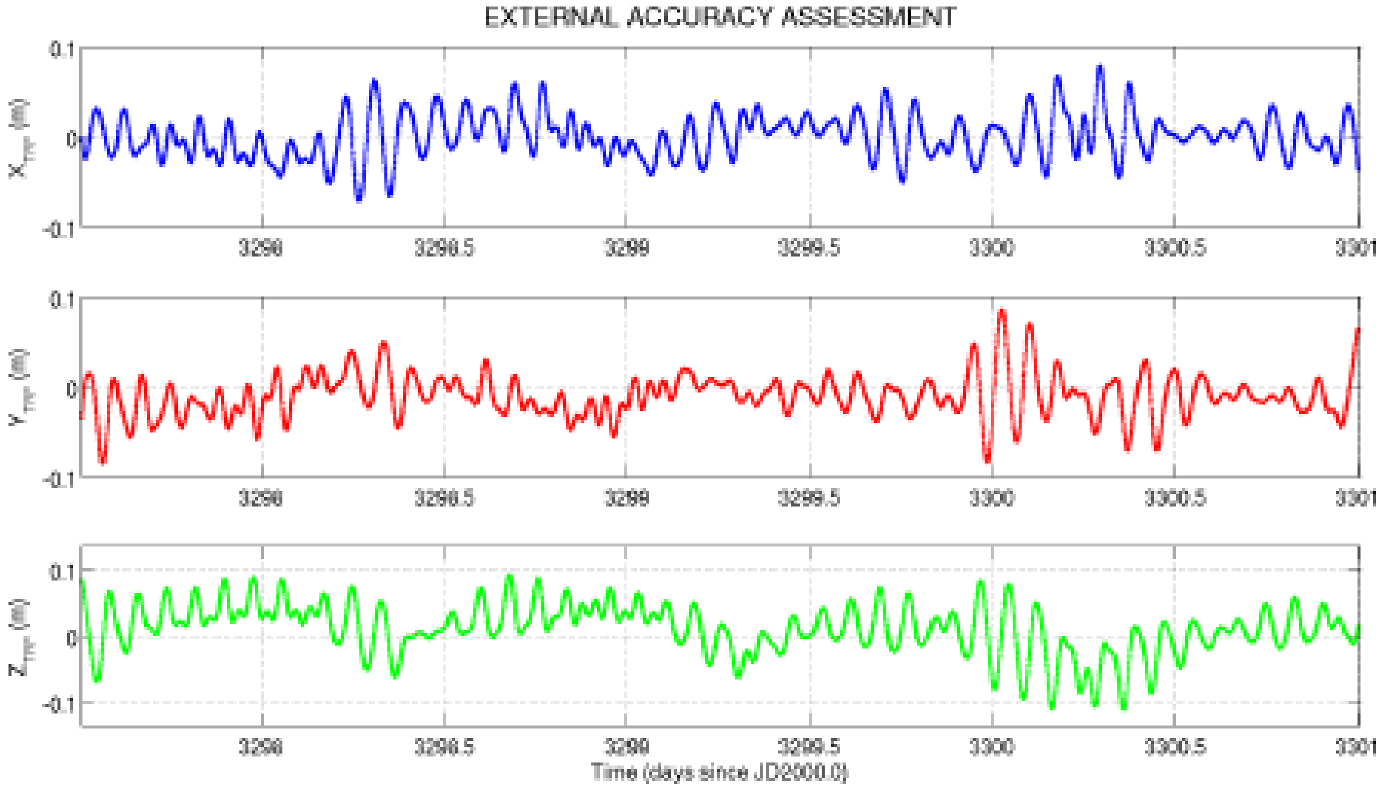
Jason-2 results (I)

- The SLR observations to Jason-2 were processed completely.
- The **internal accuracy** assessment indicates the good quality of the dynamic orbits (mean orbit RMS = 1.18 cm)



Jason-2 results (II)

- The SLR observations to Jason-2 were processed completely.
- The **external comparisons** show a good agreement with the combined SLR/DORIS orbits of ESOC (differences below 10 cm)



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)

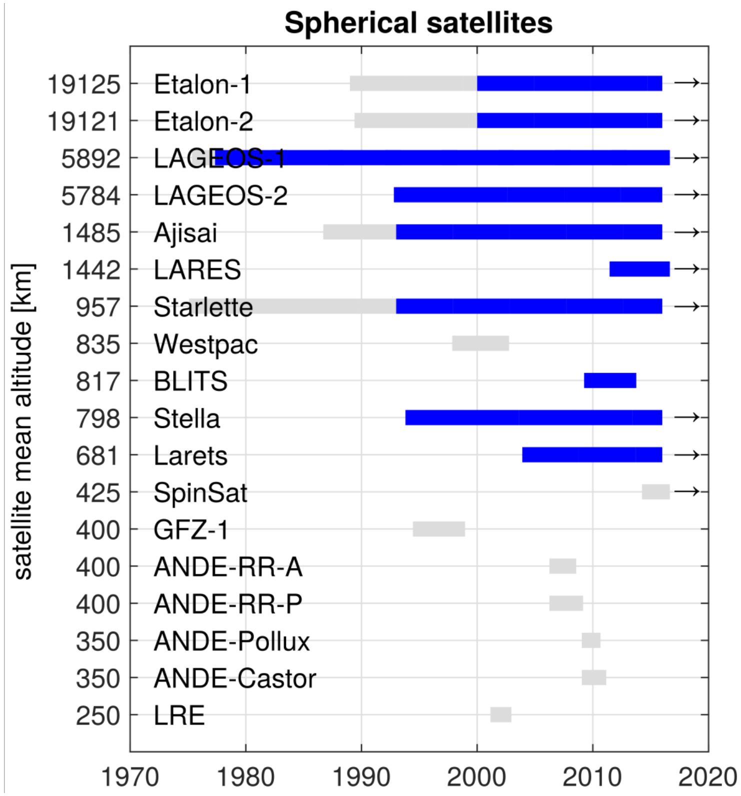
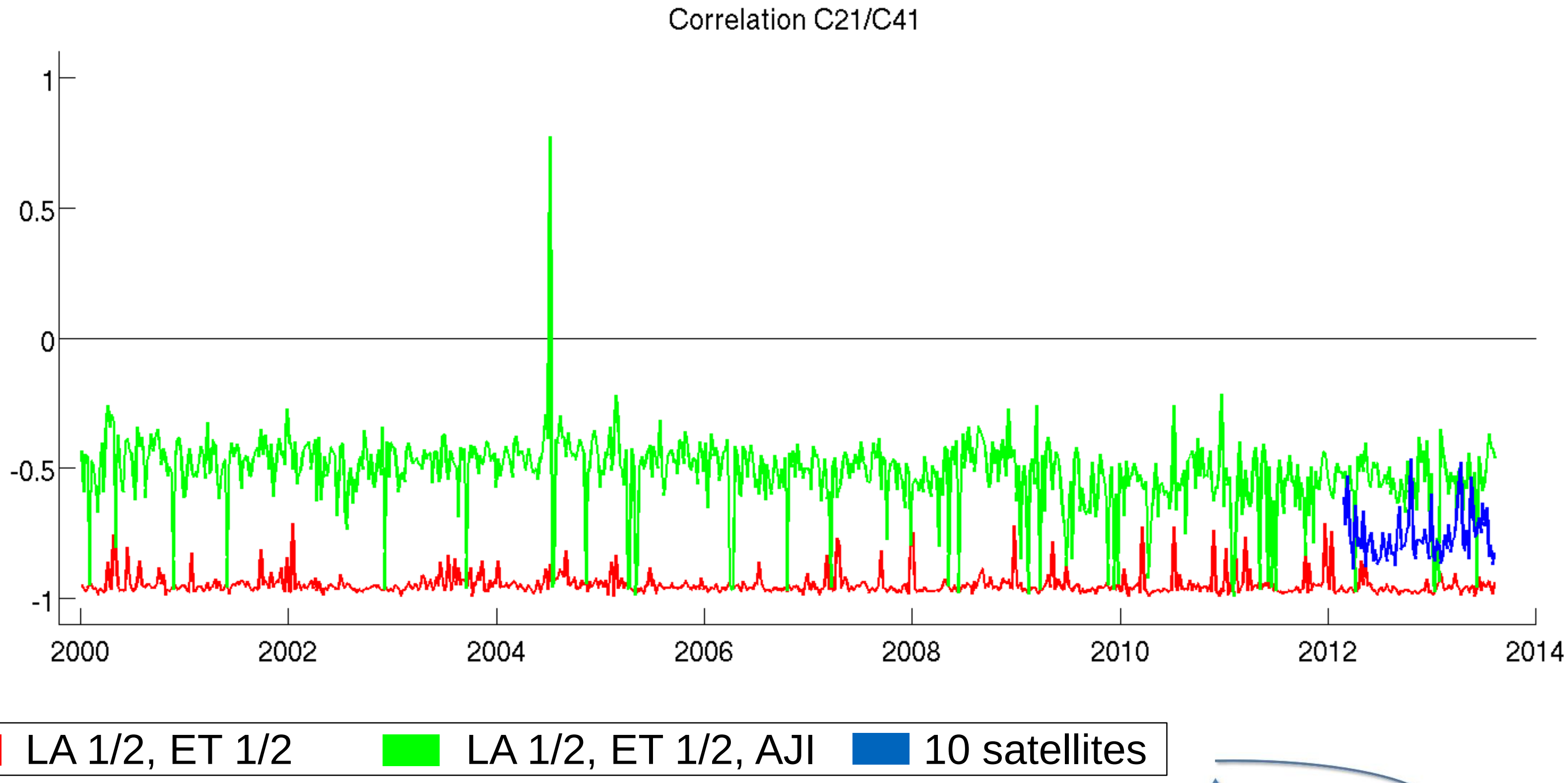


Table 8 Correlation coefficients of C_{20} and the right ascension of the ascending node of LA1 (Ω_{LA1}) at CW 51 of 2012.

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 different 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);

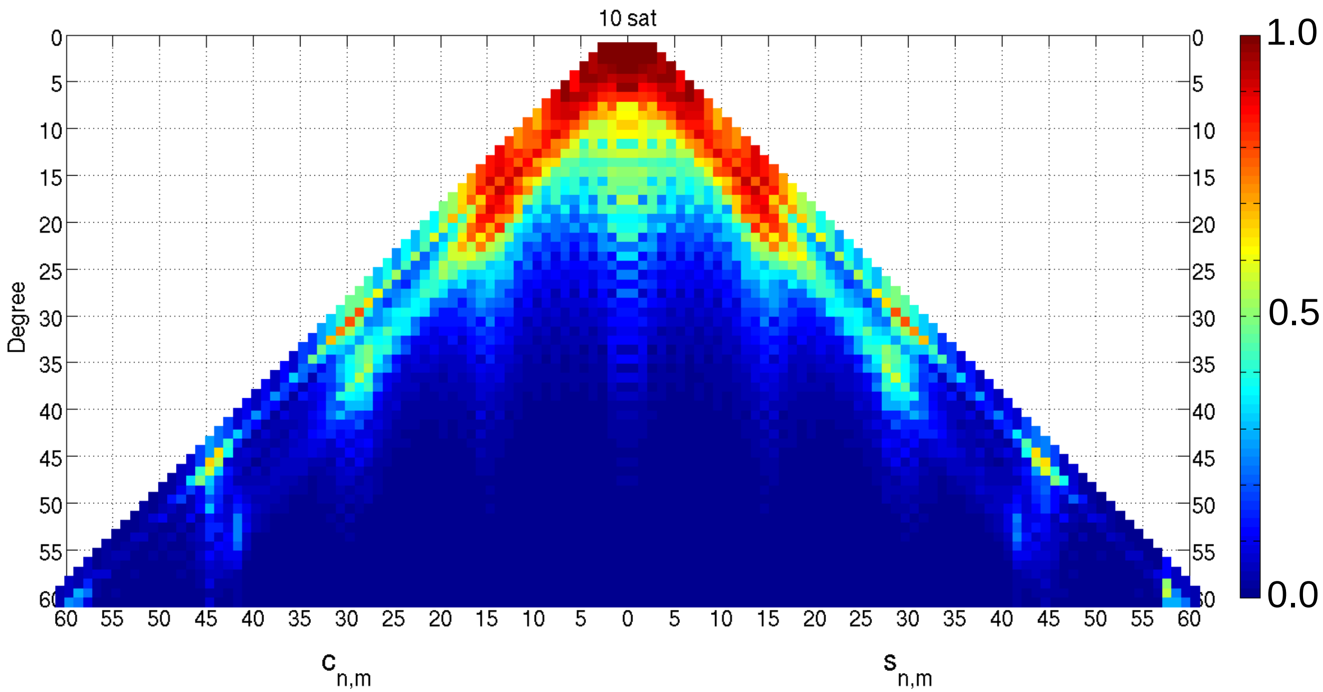
$$[0;1]\ \epsilon\ diag(N^{-1}N) = (A^T PA + \alpha K)^{-1}(A^T PA)$$

  - **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)

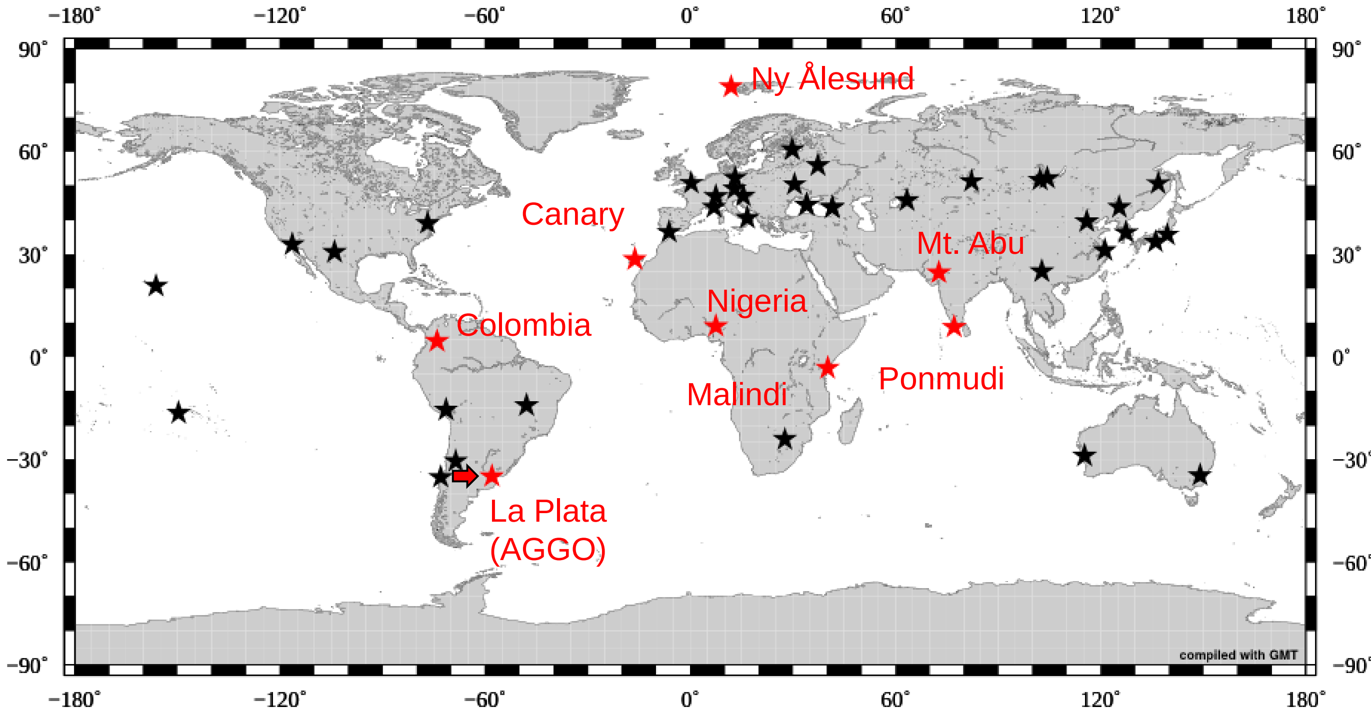
- In order to obtain reliable estimates of the Stokes coefficients, it is essential to de-correlate the orbital parameters and the coefficients of the Earth‘s gravitational field.
  - **Test 3**: Sensitivity analysis w.r.t. Stokes coefficients

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



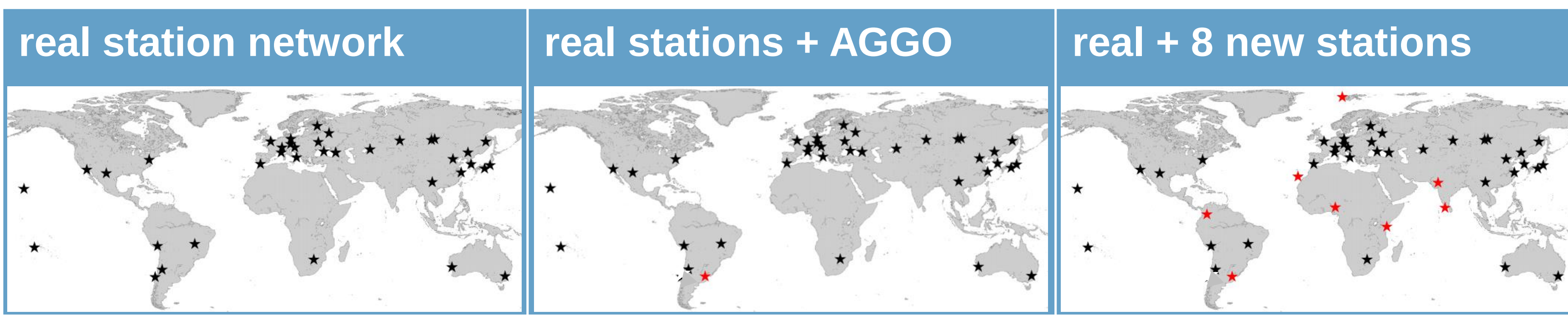
SLR simulations (I)

- DOGS-OC was developed in order to be able to simulate observations to any ground station and any satellite (e.g. LEOs, GNSS satellites, E-GRASP)
- Example: Increase of datum parameter accuracy due to eight new observing stations?



SLR simulations (II)

- Simulation setup:
  - **weekly solutions** between 01/2014 and 02/2015
  - simulated satellites: **LAGEOS 1/2, Etalon 1/2, LARES**
  - estimated parameters: **station coordinates, EOP and satellite initial state vectors**
  - **origin and scale realized implicitly** in SLR NEQs
  - **observations scheduled minimally** for orbit determination
  - **performance and noise parameters derived empirically** (no systematics assumed!)



SLR simulations (III)

- Validation of accuracy improvement by scatter of weekly similarity transformation parameters w.r.t. SLRF2008

origin [cm]	real network	real + AGGO	real + 8 new	Improvement w.r.t. real station network	
WRMS (t_x)	0.19	0.18	0.16	**7 %**	**16 %**
WRMS (t_y)	0.21	0.19	0.17	**7 %**	**18 %**
WMRS (t_z)	0.21	0.20	0.19	**5 %**	**9 %**
scale [cm]	**real network**	**real + AGGO**	**real + 8 new**		
WRMS (ρ)	0.22	0.21	0.18	**7 %**	**20 %**

➢ These numbers show the improvement of the geodetic datum purely caused by the geometric effect of a more homogeneous station network!

Conclusions and Outlook

- DOGS-OC modifications nearly finished (non-spherical sat. / refined therm. modeling)
- Jason-2 observations are analyzed; internal/external validations confirm their reliability
- Different test of SLR multi-satellite solution have been performed
  - **Test 1**: de-correlation of orbit parameters and Stokes coefficient C_{20}
  - **Test 2**: de-correlation of Stokes coefficients itself
  - **Test 3**: sensitivity analysis of satellite observations w.r.t. Stokes coefficients
- Simulation of eight new SLR stations results in an improvement of up to 20 % in the translation and scale parameter time series
- Realization of physical TRF datum will be investigated using as much as possible SLR satellites (spherical + Jason-2/SWARM-A/B/C)
- Combination of SLR and GNSS NEQs and analysis of SLR observations to GNSS satellites still pending

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Thank you for your attention! Any questions?

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Personnel situation at DGFI-TUM

- **<u>1st project phase (03/2012 – 02/2015):</u>**
- **Natasha Panafidina**
  - ➢ worked full-time for two years
  - ➢ was on parental leave for one year
  - ➢ is working half-time for two years
- **Francesca Panzetta** (parental leave substitution for Natasha)
  - ➢ worked full-time for 9 months
- **<u>2nd project phase (03/2015 – 02/2017):</u>**
- **Francesca Panzetta**
  - ➢ worked full-time for 6 months
- **Sergej Rudenko**
  - ➢ will start in August for three years (half-time)

Refined modeling of thermospheric perturbations

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

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

$\hat{\boldsymbol{u}}_D = \frac{v_{rel}}{\|v_{rel}\|}$	drag unit vector
v_{rel}	relative velocity of the satellite w.r.t. the thermosphere
C_D	thermospheric drag coefficient ($C_L, C_D = 0$ for spherical satellites)
ρ	integrated thermospheric density
A_{eff}	effective satellite cross-section area interacting with the thermosphere
m	satellite mass
$\boldsymbol{f_s}$	Lagrange scaling factor → this parameter is estimated!

➢ **How can thermospheric density corrections be computed?**

Computation of physically-based drag coefficient C_D

estimated thermospheric scaling factor

f_s

modeled C_D

ρ obtained from thermospheric models

constant/tabulated value of C_D
(historically $C_D = 2.2$ for all satellites with compact shape)

physical values, analytically computed using a gas-surface interaction (GSI) model

fitted values
(based on specific thermospheric model)

Assumptions and key parameters

Assumptions for refined thermospheric density estimation

Assumption 1 → **Free molecular flow**: no inter-molecular collisions at satellite altitudes > 150 km (based on the Knudsen number)

Assumption 2 → **Sentman's GSI model**: interaction between gas and satellite surface at altitudes < 500 km

Assumption 3 → Satellite surface is covered with a layer of absorbed atomic oxygen → **fully diffuse reflection** of the gas particles with **full accomodation** ($\alpha = 1$; explanation on next slide)

Assumption 4 → **Thermal flow**: incident flow at satellite surface is superposition of random thermal molecule velocity (Maxwell-Boltzmann distribution) and bulk velocity (v_{rel})

Assumption 5 → **Maxwell-Boltzmann velocity** of re-emitted particles

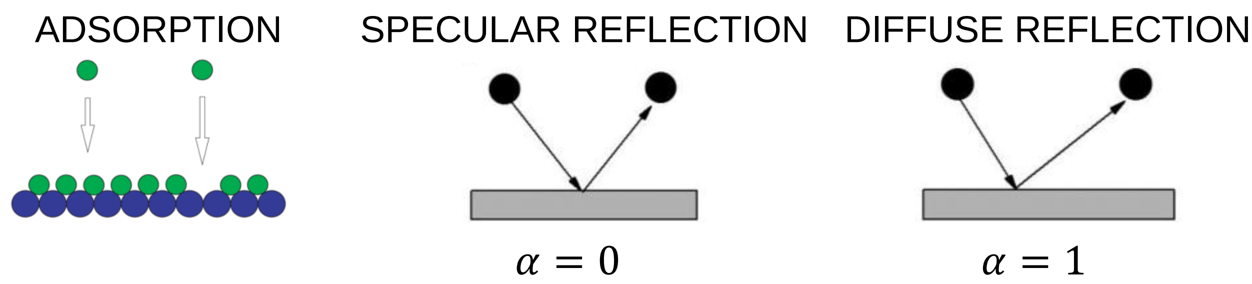
Assumption 6 → $\boldsymbol{T_w = 300\ K}$

Key parameters for refined thermospheric density est.

- Based on the assumptions, C_D can be computed according to

$$C_{D,k}^{(sp)} = \frac{4s_k^4 + 4s_k^2 - 1}{2s_k^4}\operatorname{erf}(s_k) + \frac{2s_k^2 + 1}{\sqrt{\pi}s_k^3}e^{-s_k^2} + \frac{2\sqrt{\pi}}{3 4 s_k}\sqrt{\frac{T_w}{T_\infty}}$$

Key parameter 1 →



Key parameter 2 →

E_i, E_r, E_w → kinetic energies of incident, reflected and re-emitted molecules with temperature of the surface (wall)

Key parameter 3 → Energy accommodation coefficient $\boldsymbol{\alpha = \frac{E_i - E_r}{E_i - E_w}}$ which quantifies the amount of energy exchange between gas and surface

Key parameter 4 → Satellite surface and thermospheric temperatures $\boldsymbol{T_w}$ and $\boldsymbol{T_\infty}$