Implementation and Validation of a Novel Representation of the Gravitational Effect of Ocean Tides

Alexander Kehm[1], Mathis Bloßfeld[1], Michael Hart-Davis[1], Henryk Dobslaw[2], Torsten Mayer-Gürr[3]

[1] Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Technical University of Munich, Munich, Germany
[2] Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany
[3] Graz University of Technology, Institute of Geodesy, Graz, Austria

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Ocean tides

- Tides remain a **crucial contributor** to a variety of geodetic applications, including satellite altimetry and gravimetry.

- In recent years, **significant advances** have been made in ocean tide models in terms of model accuracies as well as in model abilities to derive more tidal constituents.

- Empirical, data-driven, tide models produce the highest level of accuracy largely thanks to satellite altimetry.

- Purely hydrodynamic models are not restricted by aliasing or noise related constraints allowing them to estimate a wider range of tidal constituents.

➢ **Data formats allowing to flexibly apply different tide models in space-geodetic analysis are important!**

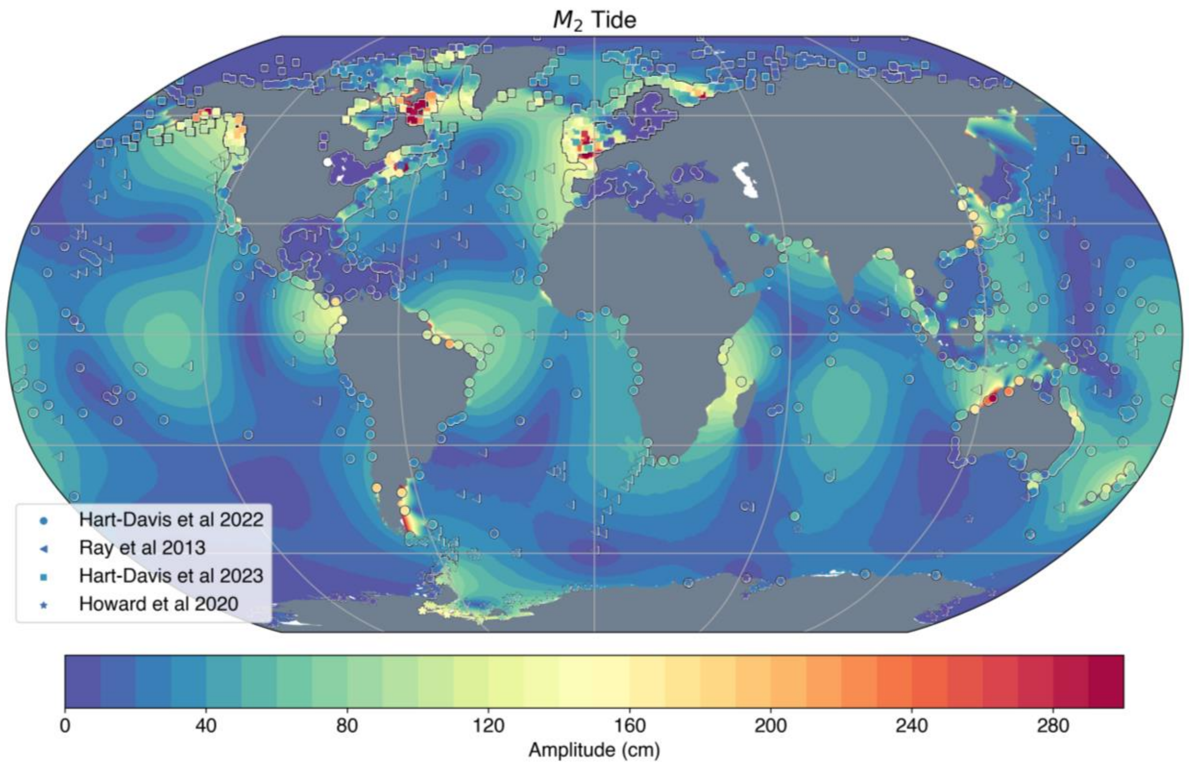


Fig. The M_2 tide from EOT20 tide model (Hart-Davis et al 2021) overlaid with data from available in-situ tidal constituent databases.

Parameterisation of the gravitational effect of ocean tides

IERS Conventions 2010 (Petit and Luzum, 2010, Sect. 6.3):

- Ocean tides are provided in the form of spherical harmonics for tide heights
- Synthesis with period-depedent phase biases (Doodson-Warburg convention; IERS Conv. 2010, Tab. 6.6)
- Tidal admittance via „hardcoded" table (adapted to the old FES2004 model; IERS Conv. 2010, Tab. 6.7)

➢ Various sources for mis-implementation
➢ Implementational effort for any new model
➢ Inconsistencies due to model-dependet ambiguous tide definitions (e.g. S1: 164.556 or 164.555)

Alternative approach (Mayer-Gürr et al., 2023) based on the standard **ICGEM format**:

- Ocean tides are provided in the form of spherical harmonics for the gravitational effect
- No phase biases
- Tidal admittance and Doodson multipliers provided in matrices

➢ Model-independent and unambiguous implementation
➢ Any tidal admittance method can be used

➢ **Implemented and tested in DOGS-OC**

Implementation

Source:
Mayer-Gürr et al. (2023): *Exploiting the full potential of ocean tide models for space geodetic techniques.* EGU General Assembly 2023, DOI 10.5194/egusphere-egu23-13235

Ocean tide synthesis at time t

$$\begin{bmatrix} c_{nm} \\ s_{nm} \end{bmatrix}(t) = \sum_k f_k^{cos}(t) \begin{bmatrix} c_{nm} \\ s_{nm} \end{bmatrix}_k^{cos} + f_k^{sin}(t) \begin{bmatrix} c_{nm} \\ s_{nm} \end{bmatrix}_k^{sin}$$

Temporal changing factors

$$f_k^{cos}(t) = \sum_f A_{k,f} \cos\theta_f(t),$$

$$f_k^{sin}(t) = \sum_f A_{k,f} \sin\theta_f(t)$$

Phase arguments for all tidal lines

$$\theta_f(t) = \sum_{i=1}^{6} D_{f,i}\, \beta_i\,(t)$$

6 Doodson arguments

Admittance matrix

1.00000e+00	0.00000e+00	0.00000e+00	…
0.00000e+00	1.00000e+00	-1.12052e-01	…
0.00000e+00	0.00000e+00	-1.48522e-03	…
…			

Matrix with Doodson multipliers

0	0	0	0	1	0
0	0	0	0	2	0
0	0	0	2	1	0
0	0	1	0	-1	-1
0	0	1	0	0	-1
…					

All tidal lines are treated in the same way
Flexible: different interpolation schemes,
adding non TGP tides, equillibrium tides, resoncances…
Fast

Do not care about

- Darwin names / Doodson codes
- Doodson-Warburg phase shifts

Comparisons

- **Solution setups:**
  - Models: **EOT11a** (Savcenko and Bosch, 2012), **EOT20** (Hart-Davis et al., 2020)
  - Resolution: Up to degree/order 30 (low), 90 (middle), 180 (high)
  - Tidal admittance: none (only main tides), 63 secondary tides (IERS Conv. 2010), 335 secondary tides

- **Satellites:**
  - LAGEOS-1 (weekly arcs)
  - LARES (weekly arcs)
  - Jason-3 (3.5-day arcs)

- **Parameterisation:**
  - solar radiation pressure scaling factor
  - atmospheric drag pwl scaling factor (LARES, Jason-3)
  - along-track pwl empirical forces (LAGEOS-1)
  - cos/sin transversal/normal empirical forces
  - station coordinates and Earth rotation parameters fixed
  - biases according to ILRS Data Handling File

Note:

- Gravitational effect of atmospheric tides not applied
- Ocean (EOT11a/Scherneck[1]) and atmospheric (Ray and Ponte, 2003) loading unchanged

[1]http://holt.oso.chalmers.se/loading/

Results: Impact of tidal admittance and resolution

- Applying tidal admittance reduces the arc RMS by multiple millimetres:

	EOT11a with	*18 main 0 secondary*	*18 main 63 secondary (IERS 2010)*	*18 main 335 secondary*
Satellite	**altitude**	**arc rms of SLR fits** [cm]		
LAGEOS-1	5850 km	1.2108	1.1931	1.1928
LARES	1450 km	3.1290	2.7630	2.7546
Jason-3	1336 km	2.5687	2.4275	2.4263

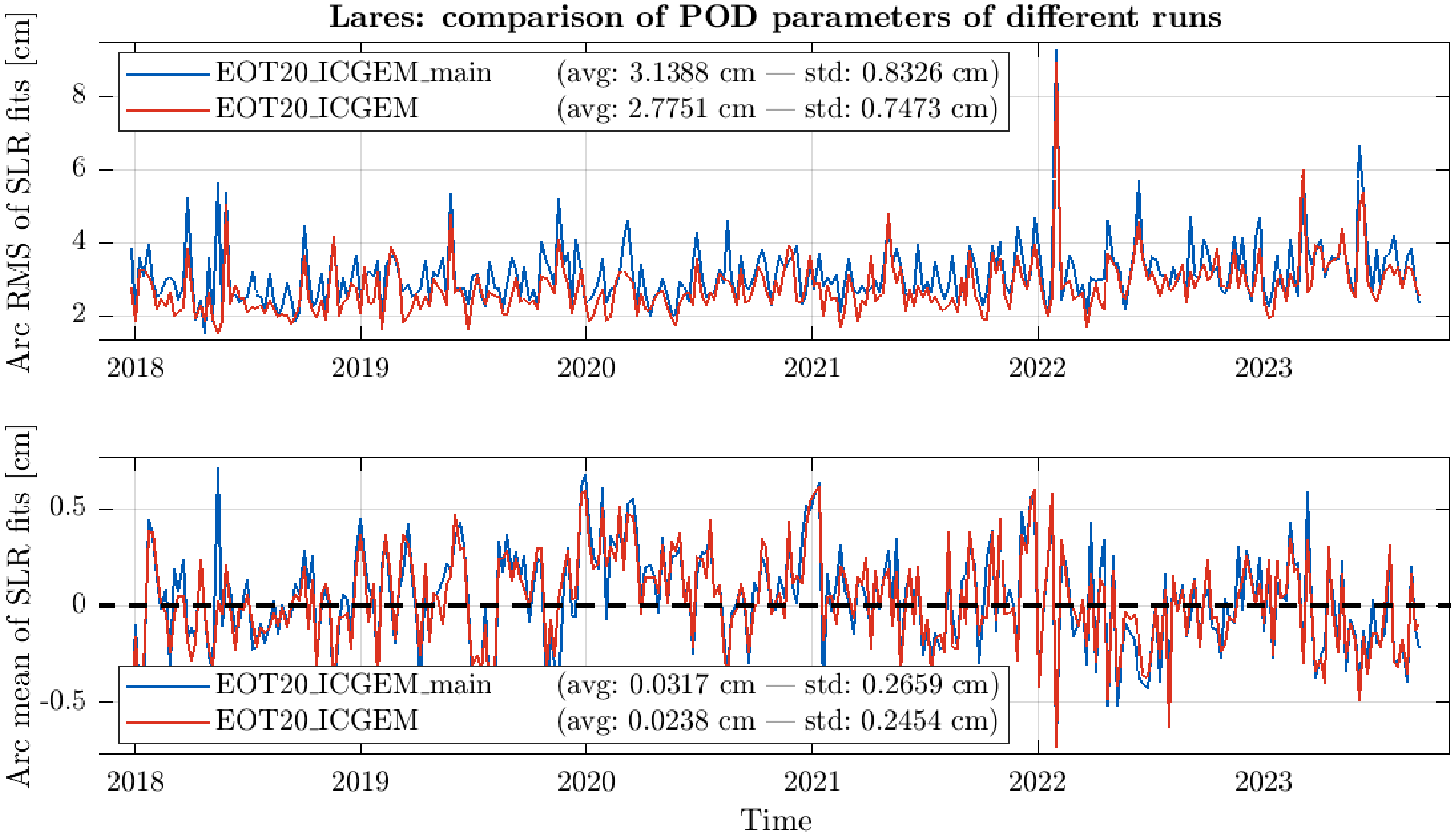
- For the satellites used in this study, the maximum degree/order (30, 90, or 180) has no significant impact on the results

- Small differences between the results for EOT11a and EOT20
  - ➢ EOT20 long-period tides could contain non-tidal loading effects which are not present in EOT11a
  - ➢ We expect that these cause the changes in SLR RMS fits

EOT20 with	*19 main 0 secondary*	*19 main 335 secondary*
Satellite	**arc rms of SLR fits** [cm]	
LAGEOS-1	1.2111	1.1939
LARES	3.1388	2.7751
Jason-3	2.5658	2.4254

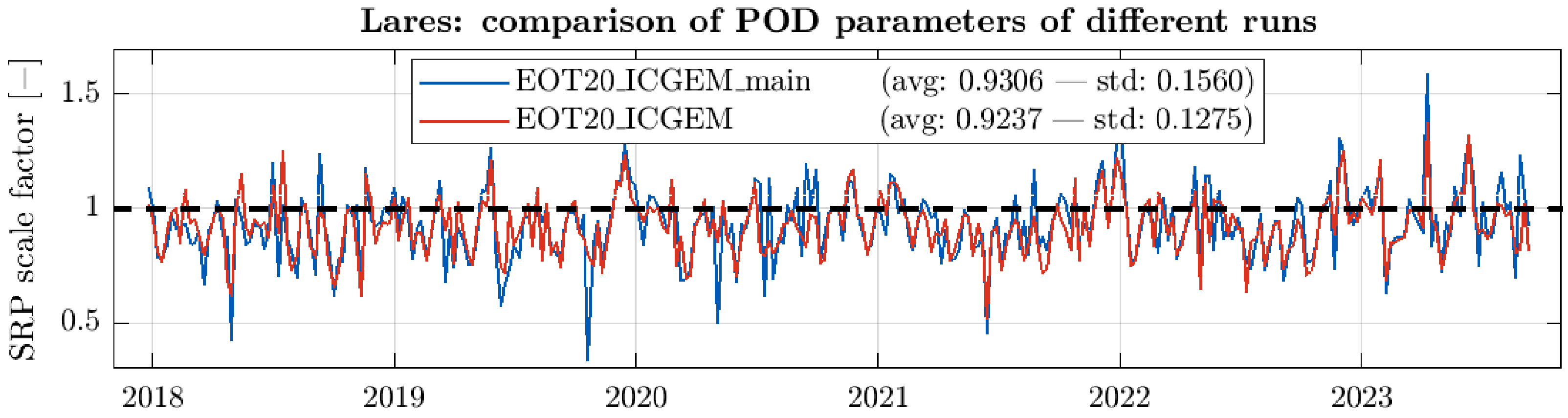
LARES: RMS of SLR fits

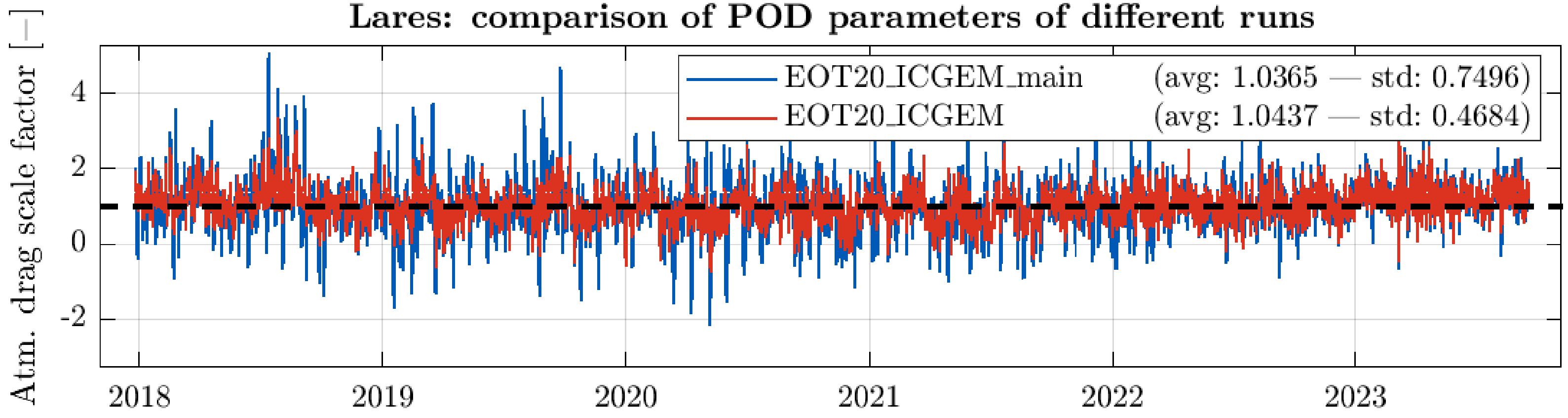
- RMS of SLR fits is reduced by several millimetres



LARES: Solar radiation pressure and atmospheric drag scale factors

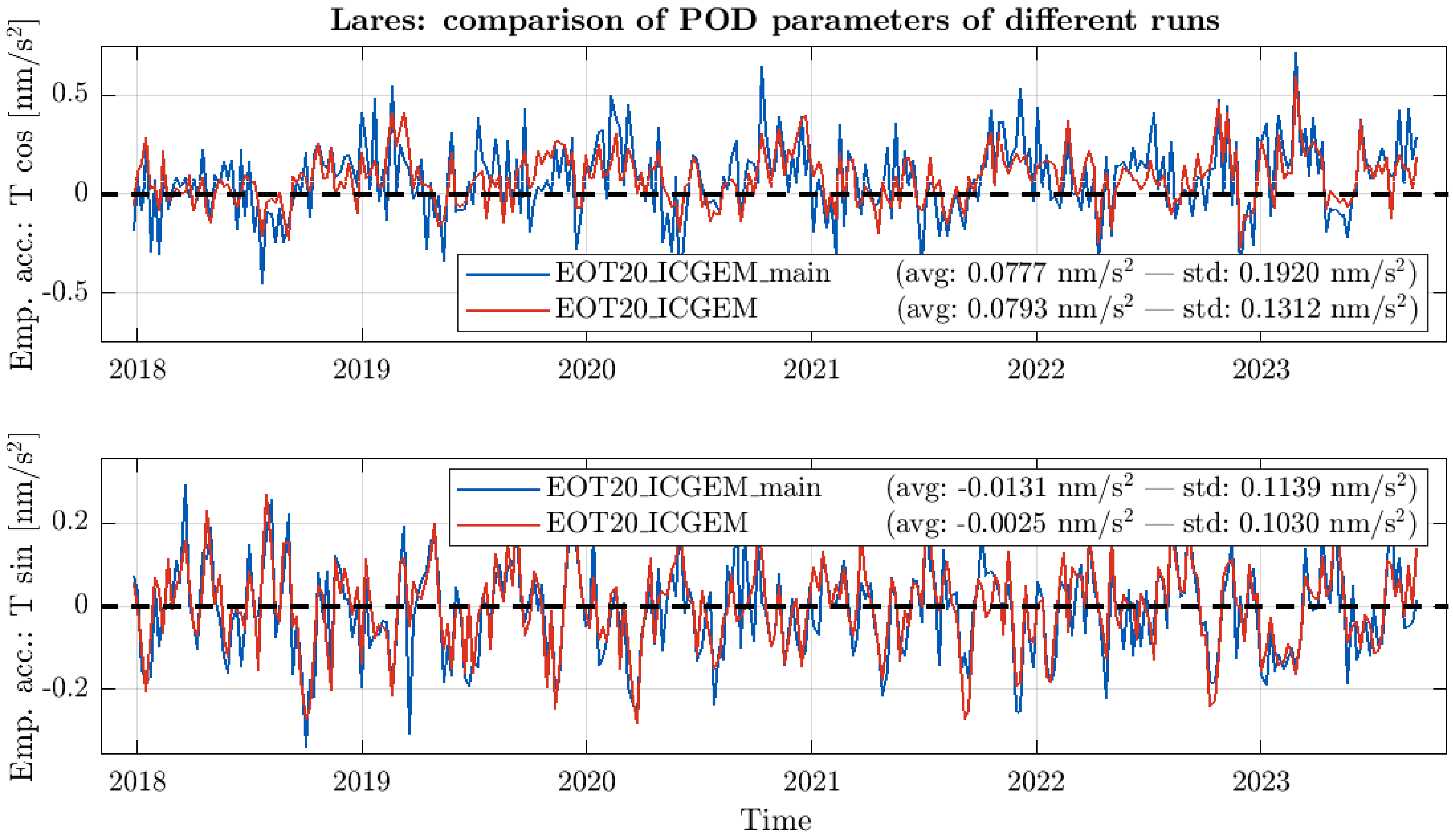
- Scatter of solar radiation pressure (SRP) and atmospheric drag scale factors is reduced





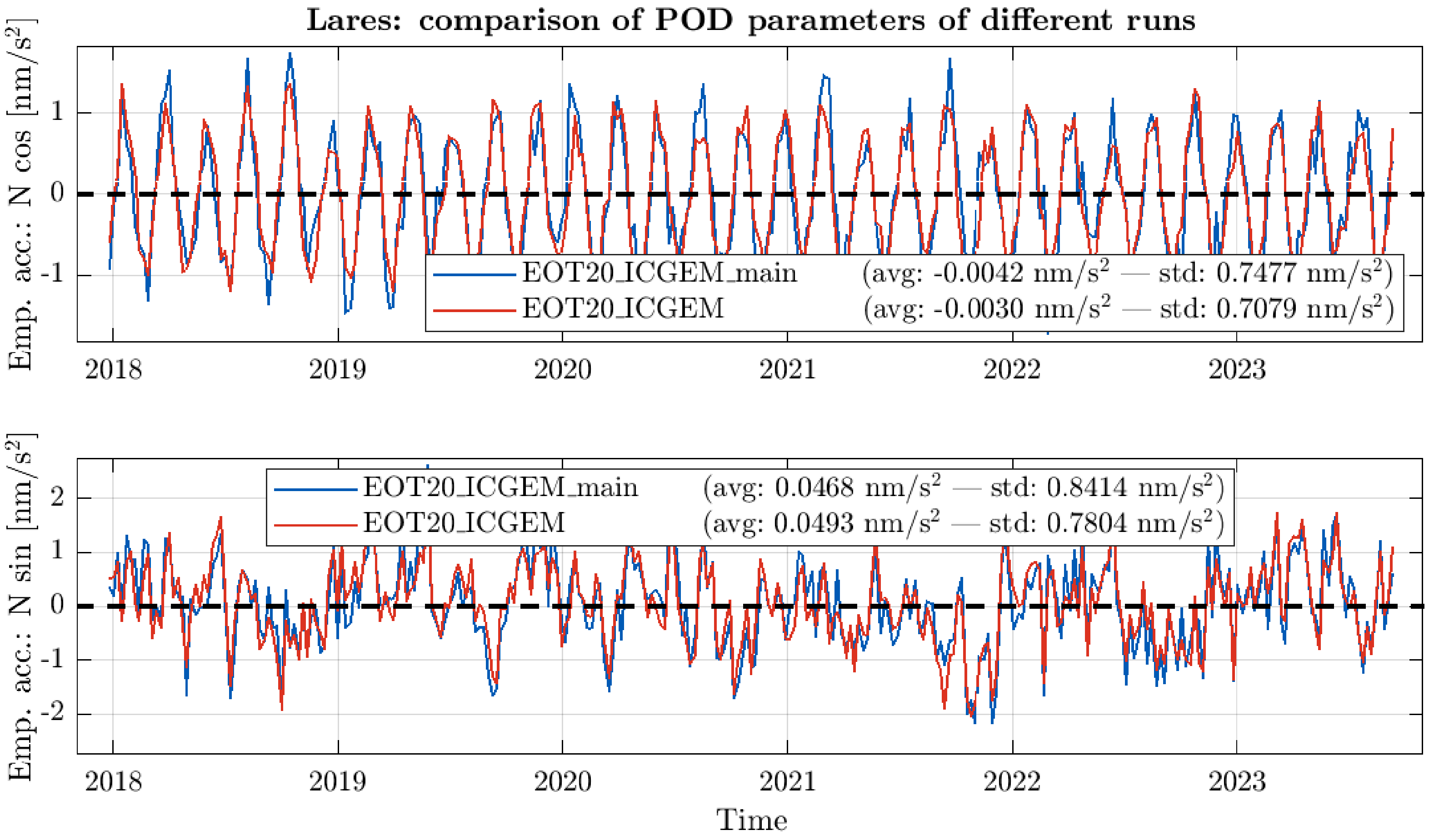
LARES: Empirical accelerations (transverse)

- Less scatter especially for the cosine component



LARES: Empirical acceleration (normal)

- Reduction in scatter for both cosine and sine component



Results: Impact of tidal admittance and resolution (EOT11a, EOT20)

	EOT20 with	*19 main 0 secondary*		*19 main 335 secondary*	
LARES					
Arc RMS	[cm]	3.1388		2.7751	
SRP scaling factor	[–]	0.9306	+/- 0.1560	0.9237	+/- 0.1275
Atmospheric drag scale factor	[–]	1.0365	+/- 0.7496	1.0437	+/- 0.4684
Emp. Acc. T cos/sin	[nm/s^2]	0.0777 0.0131	+/- 0.1920 +/- 0.1139	0.0793 -0.0025	+/- 0.1312 +/- 0.1030
Emp. Acc. N cos/sin	[nm/s^2]	-0.0042 0.0468	+/- 0.7477 +/- 0.8414	-0.0030 0.0493	+/- 0.7079 +/- 0.7804

Results: Impact of tidal admittance and resolution (EOT11a, EOT20)

	EOT20 with	*19 main 0 secondary*		*19 main 335 secondary*	
Jason-3					
Arc RMS	[cm]	2.5658		2.4254	
SRP scaling factor	[–]	0.9876	+/- 0.0315	0.9879	+/- 0.0313
Atmospheric drag scale factor	[–]	1.2766	+/- 0.8956	1.2760	+/- 0.8878
Emp. Acc. T cos/sin	[nm/s²]	0.0577 0.0115	+/- 0.5236 +/- 0.3178	0.0545 0.0234	+/- 0.4954 +/- 0.3076
Emp. Acc. N cos/sin	[nm/s²]	-0.0012 -0.0473	+/- 0.3638 +/- 0.5022	-0.0170 -0.0410	+/- 0.3289 +/- 0.4507

Results: Impact of tidal admittance and resolution (EOT11a, EOT20)

	EOT20 with	*19 main 0 secondary*		*19 main 335 secondary*	
LAGEOS-1					
Arc RMS	[cm]	1.2111		1.1939	
SRP scaling factor	[–]	1.0349	+/- 0.0340	1.0339	+/- 0.0358
Atmospheric drag scale factor	[–]	–	–	–	–
Emp. Acc. T cos/sin	[nm/s²]	0.0129 0.0001	+/- 0.0417 +/- 0.0327	0.0133 -0.0001	+/- 0.0409 +/- 0.0327
Emp. Acc. N cos/sin	[nm/s²]	-0.0027 0.0195	+/- 0.1337 +/- 0.1224	-0.0046 0.0236	+/- 0.1323 +/- 0.1138

Conclusions

The results support using ocean tide models in ICGEM format with tidal admittance matrix:

- ➢ Model-independent implementation
- ➢ Less sources of ambiguity
- ➢ Flexible matrix-based tidal admittance

- ▪ Using more interpolated secondary tides
  - ➢ reduces the SLR orbit RMS
  - ➢ stabilises or reduces extrema of empirical forces estimates
  - ➢ stabilises solar radiation/atmospheric pressure scaling factors
- ▪ For classical SLR satellites, max. degree/order 30 seems sufficient
  - ➢ should be investigated for LEOs in lower orbits

- ➢ Reduction of orbit parameters absorbing unmodelled effects will allow for a **enhanced dynamic orbit estimation.**

- ➢ ***Future work: test on other (combinations of) tide models.***

https://ifg.tugraz.at/ocean-tides

Ocean tides
- FES2014b
- EOT20, EOT11a
- TiME22
- .. Further models follow

Atmospheric tides
- TiME22
- …

Reference implementations
- MATLAB, Python, Fortran

Skripts for converting ocean tide models
- from gridded NetCDF grids to spherical harmonics
- generating all necessary files
- based on GROOPS
- https://github.com/groops-devs/groops

References

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