Ocean and Atmospheric Tide Models in SLR Precise Orbit Determination

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Ocean tides

- Tides remain a crucial contributor to a variety of geodetic applications, including satellite altimetry and gravimetry, and, e.g., precise orbit determination (POD)
- 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
- In the analysis of SLR observations, a gravitational effect (on the satellite) as well as a loading effect (on the station) has to be considered

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

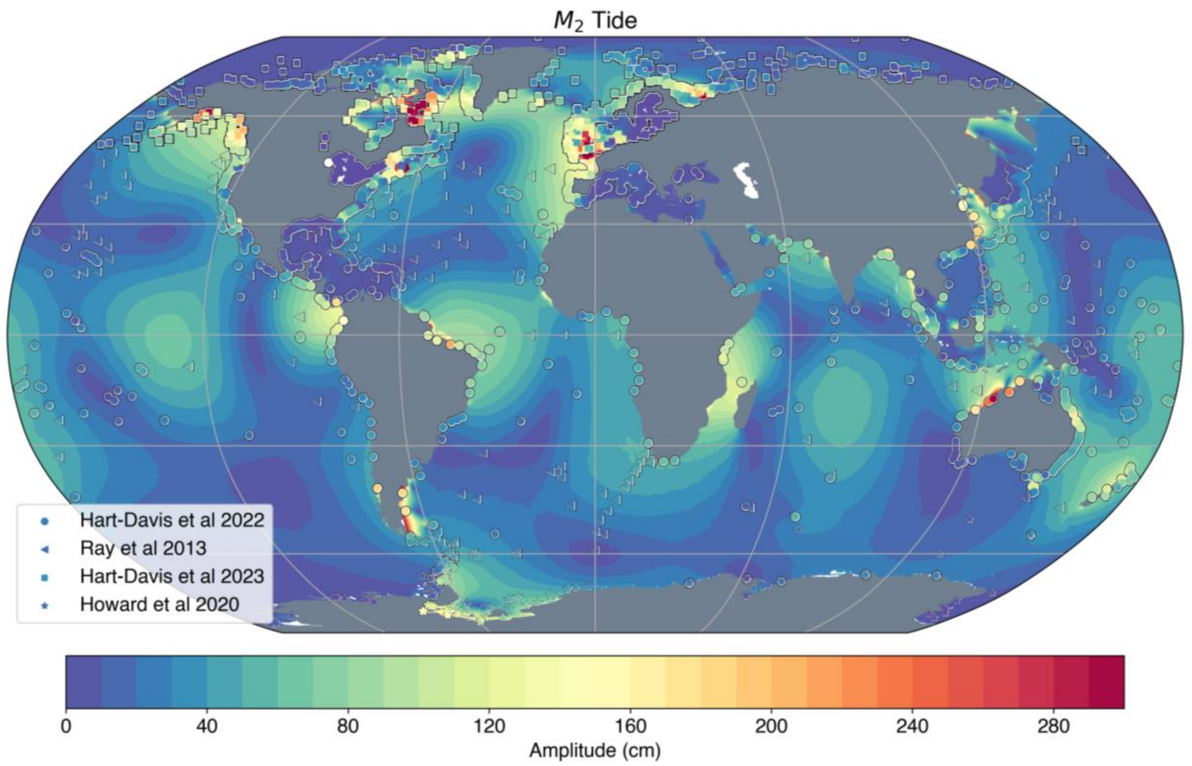


Fig. The M_2 tide from EOT20 tide model (Hart-Davis et al., 2021) overlaid with data from available in-situ tidal constituent databases.

Ocean tidal gravitational/loading deformation effect

Conventional approach (Petit and Luzum, 2010):

- Spherical harmonics for tide heights
- Period-depedent phase biases (Doodson-Warburg convention; IERS Conv. 2010, Tab. 6.6)
- Tidal admittance for gravitational effect via „hardcoded“ table (for old FES2004; IERS Conv. 2010, Tab. 6.7)
- Tidal loading (Scherneck and Bos, 2002) displacements ignore tidal admittance

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

Alternative approach (TU Graz, GFZ):

- Gravitational effect of main tides in standard ICGEM format
- Tidal loading displacement of main tides in gridded NetCDF format
- Tidal admittance and Doodson multipliers are provided in matrix form (no phase biases)

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

➢ Implemented and tested in DOGS-OC

Implementation of gravitational effect

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

Preliminary experiments

- Solution setups:
  - Models: Ocean
    - **EOT11a** (Savcenko and Bosch, 2012)
    - **EOT20** (Hart-Davis et al., 2021)
    - **TiME22** (Sulzbach et al., 2022)

    Atmosphere
    - **AOD1B RL06** (Dobslaw et al., 2017)
  - 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

- Parameterisation:
  - solar radiation pressure scaling factor (SRP)
  - Earth albedo (ALB)
  - atmospheric drag pwl scaling factor (ATD)
  - cos/sin tangential (along-track) empirical forces (ETC, ETS)
  - cos/sin normal (cross-track) empirical forces (ENC, ENS)
  - station coordinates and Earth rotation parameters fixed
  - biases according to ILRS Data Handling File

Note:
- Ocean (EOT11a/Scherneck[1]) and atmospheric (Ray and Ponte, 2003) loading unchanged

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

red: non-optimal modelling and not fully consistent

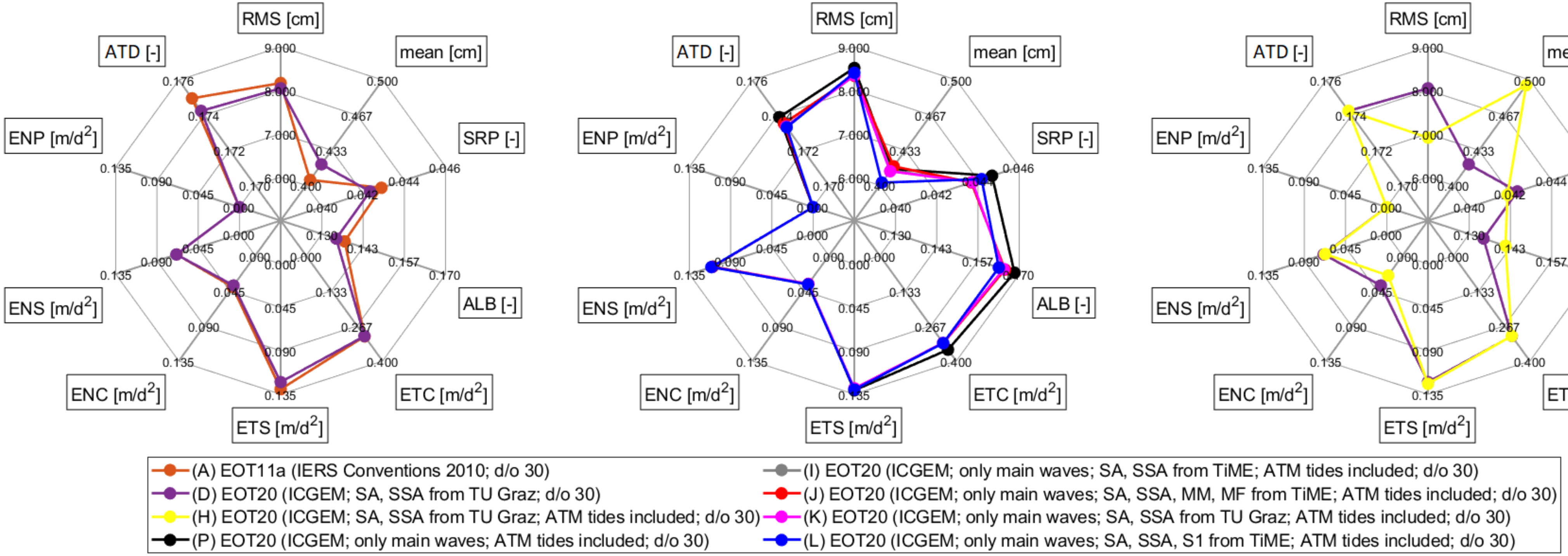
Preliminary experiments: tidal setup (ocean tide models)

	EOT	Version	Tide replacement	Admittance	ATM
(A)	EOT11a	all tides	–	IERS 2010	no
(D)	EOT20	replace →	S_a, S_{sa} (TU Graz, equilibrium tides)	335 sec. tid.	no
(H)	EOT20	replace →	S_a, S_{sa} (TU Graz, equilibrium tides)	335 sec. tid.	yes
(P)	EOT20	all tides	–	no	yes
(F)	EOT20	replace →	S_a, S_{sa} (TU Graz, equilibrium tides)	no	no
(K)	EOT20	replace →	S_a, S_{sa} (TU Graz, equilibrium tides)	no	yes
(I)	EOT20	replace →	S_a, S_{sa} (TiME22)	no	yes
(L)	EOT20	replace →	S_a, S_{sa}, S_1 (TiME22)	no	yes
(J)	EOT20	replace →	S_a, S_{sa}, M_m, M_f (TiME22)	no	yes

- Test impact of applied tidal admittance (interpolation of secondary tides).
- Test combined models (replacement of tidal constituents).
- Test impact of AOD1B RL06 (ATM; 12 atmospheric tides applied; non-tidal part omitted).

Preliminary experiments: POD results (1)

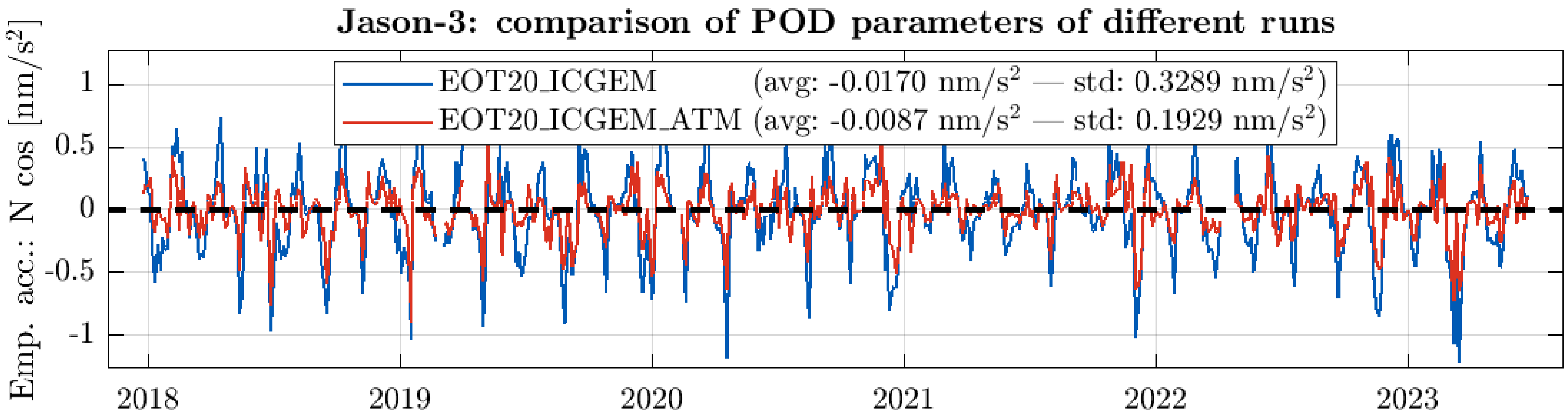
impact of EOT20 vs EOT11 | impact of 2ndary tides changed | impact of atmospheric tides



Larets SLR POD parameter standard deviations:

- EOT11a vs. EOT20 (left),
- replace (sub-groups of) S_a, S_{sa}, M_m, M_f and S_1 from EOT20 to TU Graz or TiME22 (middle),
- include the 12 atmospheric tides from AOD1B RL06 (right).

Preliminary experiments: POD results (2)



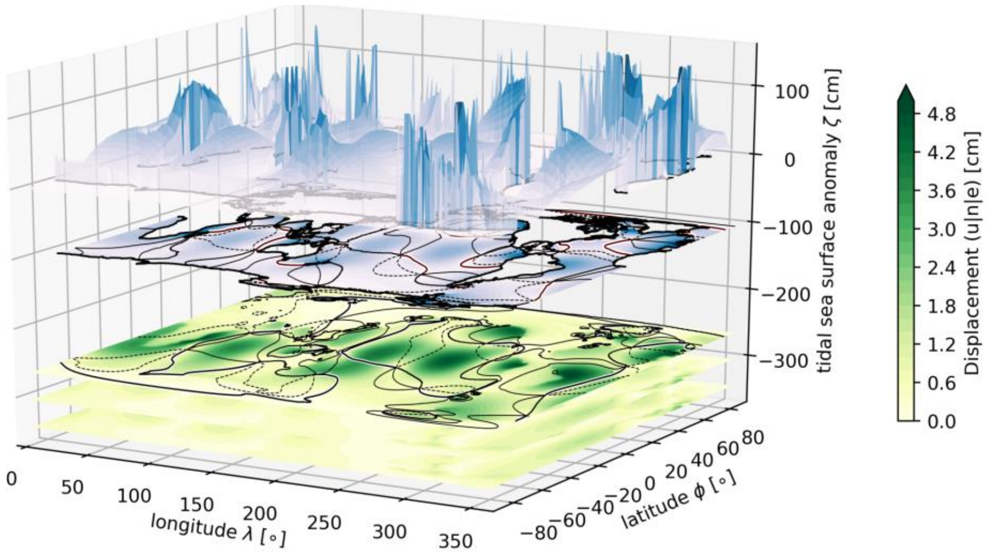
Jason-3 SLR POD empirical accelerations (normal cosine):

- impact of including the 12 atmospheric tides from AOD1B RL06,
- the amplitude of variation is significantly reduced.

Ocean tidal loading displacements

- Ocean tidal displacements of the terrestrial surface systemically affect measurements by space-geodetic techniques
  - ➢ smaller significance than tidal gravitational perturbations
  - ➢ effect is independent of the satellite orbit height

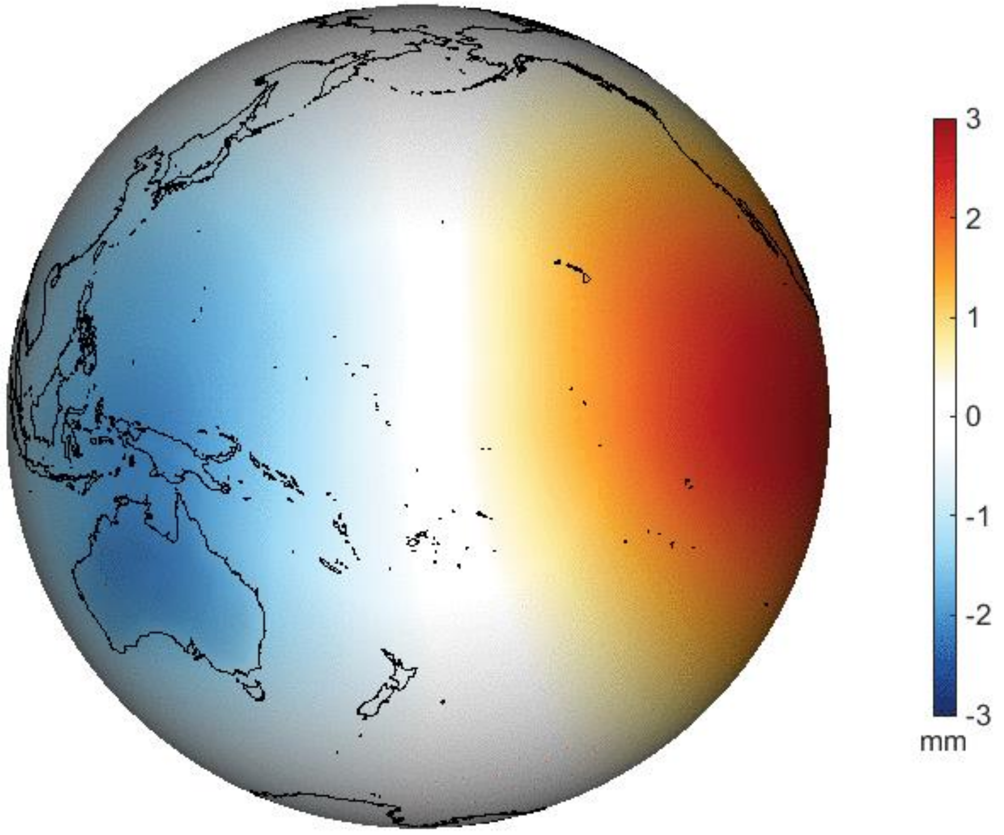
- Modeling of displacements consistent with the applied gravitational effects finished
  - ➢ ocean tide-induced surface displacements (in up|north|east direction) are derived from the same tidal surface loads used to compute the utilized tidal gravity anomalies provided in ICGEM format
  - ➢ i.e., same phase convention and consistent application of admittance theory
  - ➢ interpolated to 10000x5000 Gaussian grid
  - ➢ ESA CCI land-cover map (land/sea-mask) with extrapolation of tidal load
  - ➢ Spherical harmonic decomposition degree and order 5000 (Schaeffer 2013)
  - ➢ application of PREM load Love Numbers
  - ➢ data format: gridded NetCDF data
  - ➢ uncert. < 1% signal (coastal); else <<1%



Klemann et al. (2024)

Atmospheric tidal displacements

- Most prominent periods 12 h and 24 h (but also other periods exist)
- Accounting for such effects decreases aliasing and reduces spurious effects (Balidakis et al., 2022)
- To date, atmospheric tidal displacement models agree at a level of 0.2 mm for individual tides
- Consistency between ocean and atmospheric tide models must be ensured (estimated tidal components, distribution of signal content)
- Using the atmospheric tides from AOD1B RL06 together with EOT20/TiME22 combined models is not optimal



TAL displacement at 00:00:00

Conclusions and outlook

- Applying recent tidal models with appropriate tidal admittance
  - ➢ reduces the SLR orbit RMS
  - ➢ stabilises or reduces extrema of empirical forces estimates
  - ➢ stabilises solar radiation/atmospheric pressure scaling factors

- Satellite-data-constrained ocean tide models are expected to be less accurate for radiationally-impacted and small-amplitude tides (e.g., S_{sa}, S_a, S_1, and $^3M_3$) due to the reduced quality of data

- Purely hydrodynamical models are independent of observations and might produce more accurate prediction in these cases

- The results suggest that combinations of both model types are suitable to achieve best POD results

- Further experiments for consistent application of ocean and atmospheric tidal gravitational and loading currently running
  - ➢ consistent ocean tide models for gravitational and loading effects
  - ➢ consistent tidal atmospheric models for both effects
  - ➢ consistent non-tidal ocean and atmospheric models for both effects

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

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

Atmospheric tides
- TiME22
- …

Reference implementations
- MATLAB, Python, Fortran

Scripts 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