On ocean tide background modelling during GRACE gravity field determination

Christoph Dahle[1], Roman Sulzbach[1], Markus Hauk[1],
Torsten Mayer-Gürr[2]

[1]GFZ Helmholtz Centre for Geosciences
[2]Graz University of Technology, Institute of Geodesy

GRACE-FO 2025 Science Team Meeting,
online, 7-9 October 2025

GFZ Helmholtz Centre for Geosciences

HELMHOLTZ

Ocean tides in the context of GRACE

- Inevitable background model to reduce tidal signals from observations and minimize temporal aliasing errors
- Different global ocean tide models are available
  - Total number of contained tidal constituents may differ
  - Missing minor tides → interpolation using admittance theory is used
- Tests and model comparisons are usually performed by GRACE processing centers prior to each new release
- A crash course on ocean tides is provided in the EGU2023 presentation by Mayer-Gürr et al.[1], available at:

  https://presentations.copernicus.org/EGU23/EGU23-13235_presentation.pdf

[1]Mayer-Guerr, T., Oehlinger, F., Sulzbach, R., and Dobslaw, H.: Exploiting the full potential of ocean tide models for space geodetic techniques, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-13235, https://doi.org/10.5194/egusphere-egu23-13235, 2023.

Current status regarding ocean tide models

- Only tidal atlases are provided by modellers
  - Mostly, conversion from gridded to spherical harmonic domain is required by users
  - Admittance implementation is also on user side
- Unclear formulas & definitions for non-experts, not straight forward
  - IERS conventions only for old FES2004
  - Complicated phase definition
    - Doodson-Warburg, needs additional tables
    - ambiguous definitions for S1 (164.556 or 164.555?), minor tides

➢ Each new ocean tide model requires adjustment of source code

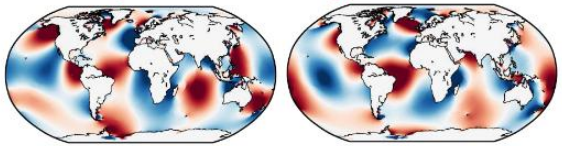
New unified approach for tidal corrections

- Goal: Facilitate a user-friendly and model-independent framework for tidal corrections
- Dedicated webpage: https://www.tugraz.at/institute/ifg/downloads/ocean-tides
  - Current status of provided models:
    - 8 ocean tide models (GOT5.6, FES2022, FES2014b, TPXO10, EOT20, EOT11a, DTU23, TiME22) + 1 mixed ocean tide model (MIXED2025: GOT5.6 extended by FES2022 & TiME22)
    - 1 atmospheric tide model (TiME22)
    - Each model is represented by **3 files** + **additional files with Stokes coefficients** for the corresponding tidal constituents
  - Reference implementations in MATLAB, Python and Fortran are provided, too

New unified approach for tidal corrections

- Ocean tide synthesis at time t

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



Coefficients from the tidal atlas

- Standard ICGEM format (*.gfc)
  - eot20_055.565_om1_cos.gfc
  - eot20_055.565_om1_sin.gfc
  - eot20_055.575_om2_cos.gfc
  - eot20_055.575_om2_sin.gfc
  - eot20_056.554_sa_cos.gfc
  - eot20_056.554_sa_sin.gfc
  - …

File 1: List with names of *.gfc-files

New unified approach for tidal corrections

- 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   …
…
```

File 3

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
…
```

File 2

- 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

Results: Overview

- Proposed unified approach has been implemented in GFZ's EPOS-OC software
- Impact of different ocean tide models on monthly gravity field solutions is assessed based on GFZ RL07p V1 solutions (see GSTM2025 presentation by M. Hauk et al.)
- Assessment criteria:
  - Analysis of KBR post-fit residuals
    - KBR range-acceleration residuals are derived from range-rate residuals, filtered with a CRN filter with 10 mHz cut-off frequency (passband between 0.37 mHz or 2/rev. and 10 mHz), and binned onto a 3×3 degree global grid
    - Variance differences per bin are evaluated: $Var(res_{OT\_Model\_1}) - Var(res_{OT\_Model\_2})$
    - Negative values: OT_Model_1 is better, positive values: OT_Model_2 is better
  - Ocean RMS of resulting gravity field solutions

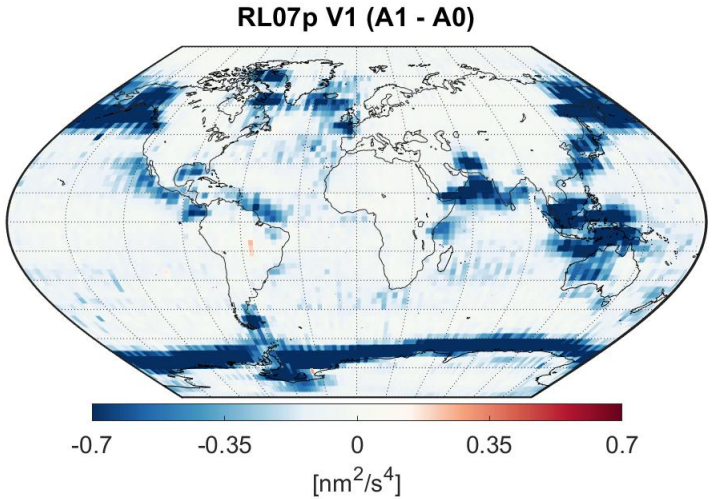
Results: 1) General ocean tide considerations

- Systematic assessment using the following models (test year 2007):
  - **Model A0**: GOT5.6 without degree-3 tides (22 tides), no admittance
  - **Model A1**: A0, linear admittance for 331 tides
  - **Model A2**: A0 + 11 degree-3 tides from TiME22, linear admittance for 407 tides
  - **Model A3**: A2 + 5 HF-radiational tides from TiME22, linear admittance for 407 tides
  - **Model A4**: A3 + 13 minor tides from FES2022/TiME22, linear admittance for 390 tides
  - **Model A5**: A4 – 3 nonlinear minor tides from FES2022, linear admittance for 390 tides + 24 nonlinear tides

Results: 1) General ocean tide considerations

A0 vs. A1

KBR range-acceleration post-fit residuals



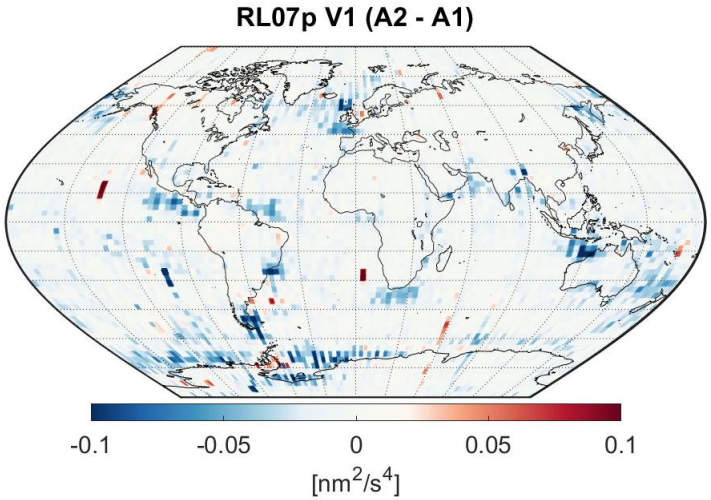
- Omitting minor tides by not applying admittance at all significantly deteriorates gravity field results

Month	Ocean RMS [cm EWH]	
	A0	A1
2007/01	4.43	**3.56**
2007/02	4.64	**3.60**
2007/03	4.05	**3.25**
2007/04	4.60	**3.58**
2007/05	4.02	**3.10**
2007/06	4.36	**3.29**
2007/07	4.04	**3.23**
2007/08	3.78	**3.00**
2007/09	4.29	**3.44**
2007/10	5.00	**3.48**
2007/11	5.13	**3.79**
2007/12	4.13	**3.32**

Results: 1) General ocean tide considerations

A1 vs. A2

KBR range-acceleration post-fit residuals



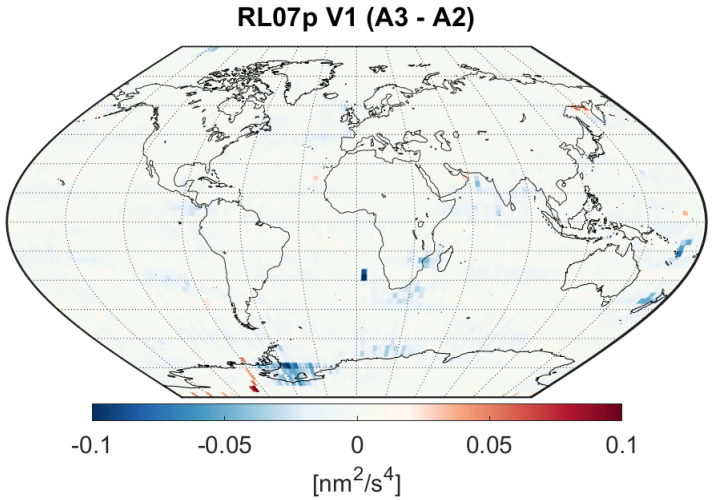
- Adding degree-3 tides from TiME22 slightly reduces global ocean RMS, but clearly improves modelling in various regions

Month	Ocean RMS [cm EWH]	
	A1	A2
2007/01	3.56	**3.44**
2007/02	3.60	**3.48**
2007/03	3.25	**3.20**
2007/04	3.58	**3.51**
2007/05	3.10	**3.06**
2007/06	3.29	**3.20**
2007/07	3.23	**3.15**
2007/08	3.00	**2.96**
2007/09	3.44	**3.40**
2007/10	3.48	**3.43**
2007/11	3.79	**3.75**
2007/12	3.32	**3.25**

Results: 1) General ocean tide considerations

A2 vs. A3

KBR range-acceleration post-fit residuals



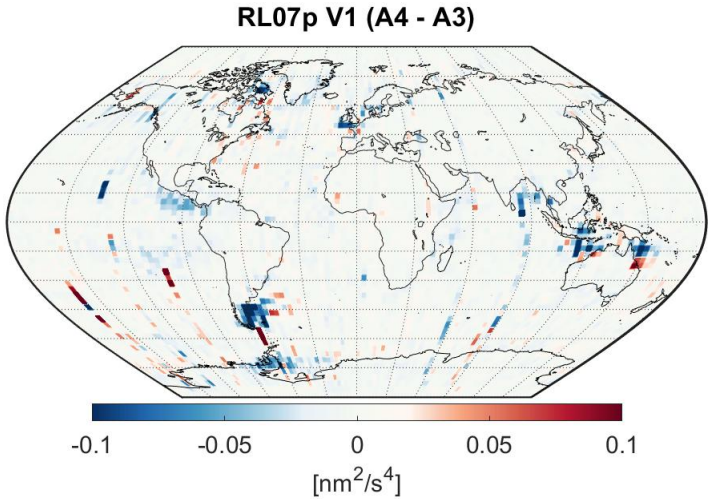
- Additionally adding HF-radiational tides from TiME22 improves modelling, mainly in the Weddell Sea; global ocean RMS hardly affected

Month	Ocean RMS [cm EWH]	
	A2	A3
2007/01	3.44	3.44
2007/02	3.48	3.48
2007/03	3.20	3.20
2007/04	3.51	3.51
2007/05	3.06	**3.05**
2007/06	3.20	3.20
2007/07	3.15	3.15
2007/08	**2.96**	2.97
2007/09	3.40	3.40
2007/10	3.43	3.43
2007/11	3.75	**3.74**
2007/12	3.25	**3.24**

Results: 1) General ocean tide considerations

A3 vs. A4

KBR range-acceleration post-fit residuals



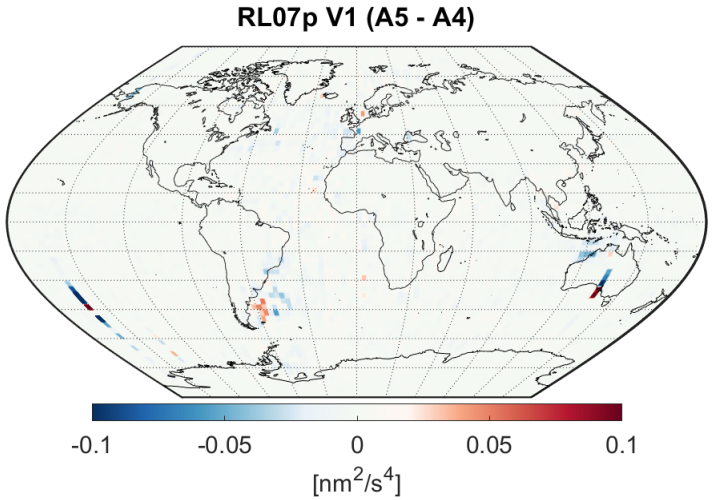
- Adding more minor tides from models instead of interpolating them further improves modelling in some regions; global ocean RMS hardly affected

Month	Ocean RMS [cm EWH]	
	A3	A4
2007/01	3.44	**3.43**
2007/02	3.48	**3.43**
2007/03	3.20	**3.18**
2007/04	3.51	**3.47**
2007/05	**3.05**	3.06
2007/06	**3.20**	3.21
2007/07	**3.15**	3.17
2007/08	2.97	**2.95**
2007/09	3.40	**3.37**
2007/10	3.43	**3.42**
2007/11	3.74	**3.73**
2007/12	3.24	**3.20**

Results: 1) General ocean tide considerations

A4 vs. A5

KBR range-acceleration post-fit residuals



- Adding linear admittance also for nonlinear minor tides has no clear influence on modelling and gravity field solutions

Month	Ocean RMS [cm EWH]	
	A4	A5
2007/01	3.43	3.43
2007/02	**3.43**	3.47
2007/03	3.18	**3.16**
2007/04	**3.47**	3.50
2007/05	3.06	**3.05**
2007/06	3.21	**3.19**
2007/07	3.17	**3.15**
2007/08	2.95	2.95
2007/09	3.37	3.37
2007/10	**3.42**	3.44
2007/11	3.73	**3.70**
2007/12	**3.20**	3.21

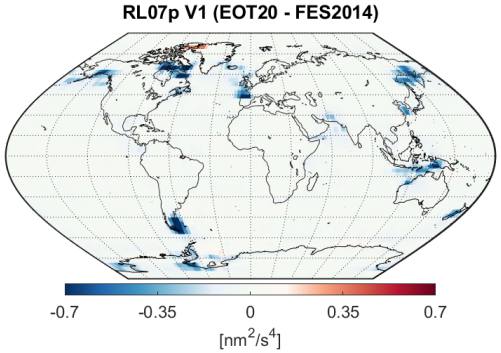
Results: 2) Ocean tide model for GFZ RL07

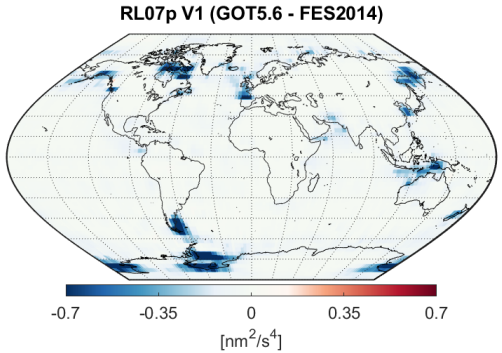
- Several ocean tide models have been tested for the years 2007 (GRACE) and 2020 (GRACE-FO)
  - Reference case: FES2014 (same model as used for GFZ RL06)
    - Original EPOS-OC ocean tide implementation incl. hard-coded admittance (limited number of only 54 interpolated tides)
  - New models tested: EOT20, FES2022, GOT5.6, MIXED2025
    - New ocean tide implementation based on unified approach

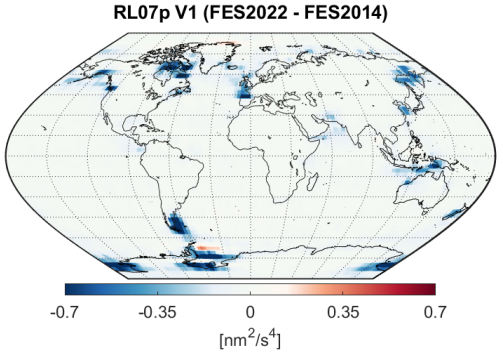
Results: 2) Ocean tide model for GFZ RL07

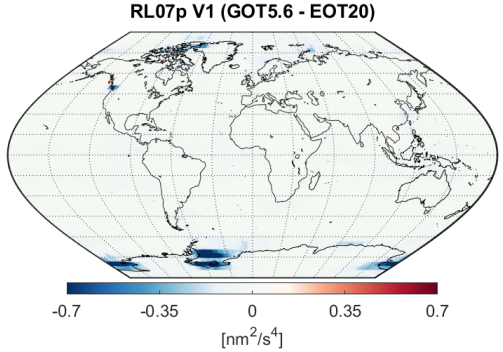
GRACE-FO

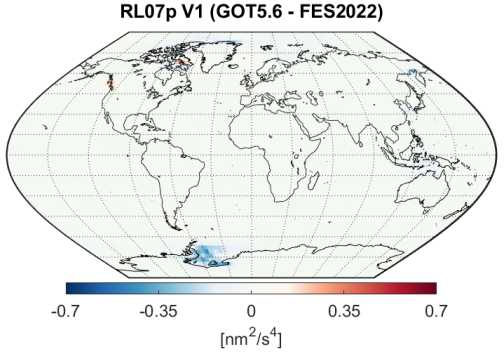
KBR range-acceleration post-fit residuals









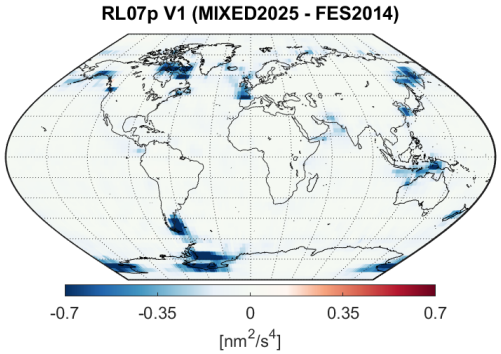


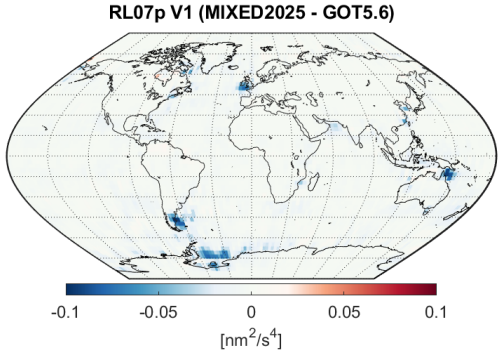
GFZ Helmholtz Centre for Geosciences

Results: 2) Ocean tide model for GFZ RL07

GRACE-FO

KBR range-acceleration post-fit residuals





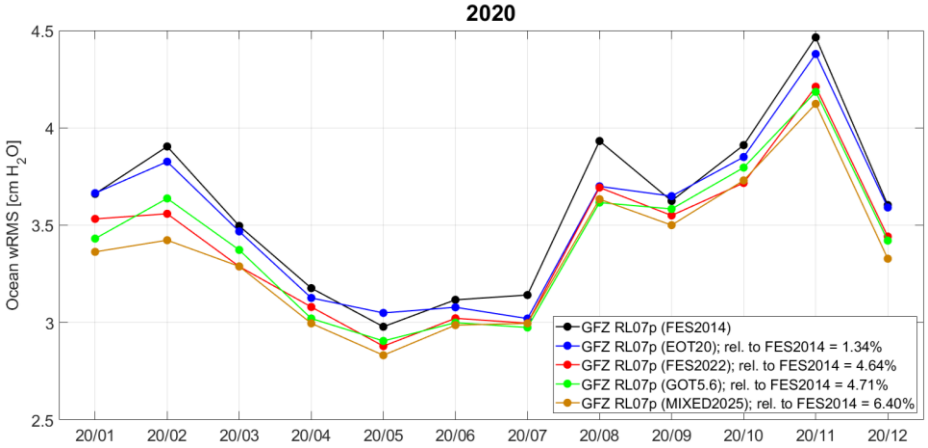
note different scale of color bar

Model	σ of residuals [nm/s²]
FES2014	0.478
EOT20	0.448
FES2022	0.422
GOT5.6	0.410
MIXED2025	0.407

Results: 2) Ocean tide model for GFZ RL07

GRACE-FO

Ocean RMS

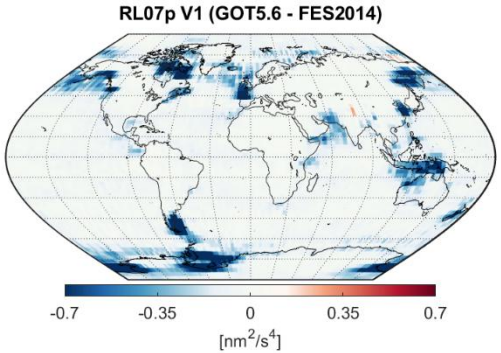


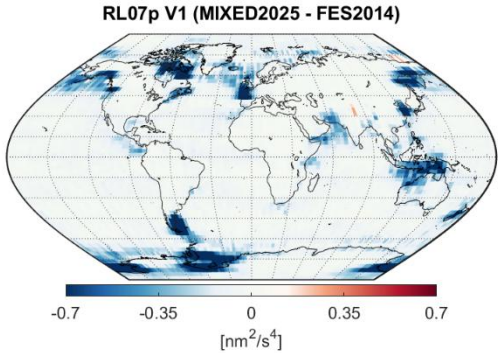
- All new models perform better than FES2014
- FES2022, GOT5.6 and MIXED2025 perform better than EOT20
- FES2022 and GOT5.6 perform similar with advantages for GOT5.6 in the Weddell Sea
- MIXED2025 performs best in terms of smallest ocean RMS and also shows reduced residual variance in a few coastal regions compared to GOT5.6

Results: 2) Ocean tide model for GFZ RL07

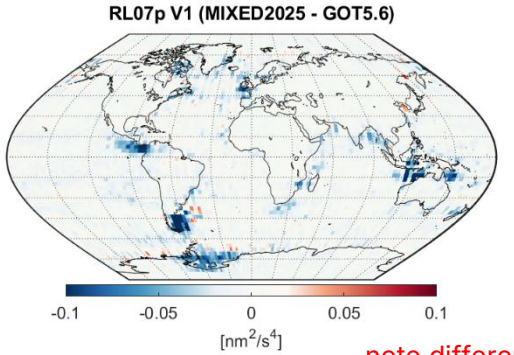
GRACE

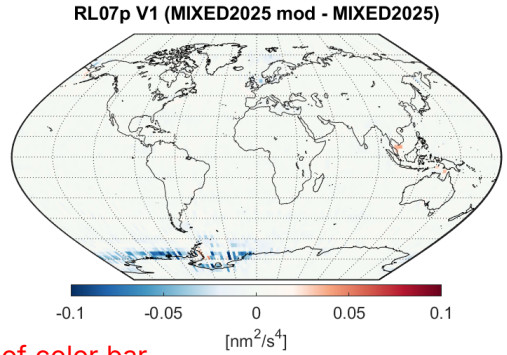
KBR range-acceleration post-fit residuals





Model	σ of residuals [nm/s²]
FES2014	0.769
GOT5.6	0.691
MIXED2025	0.687
MIXED2025 mod	0.686





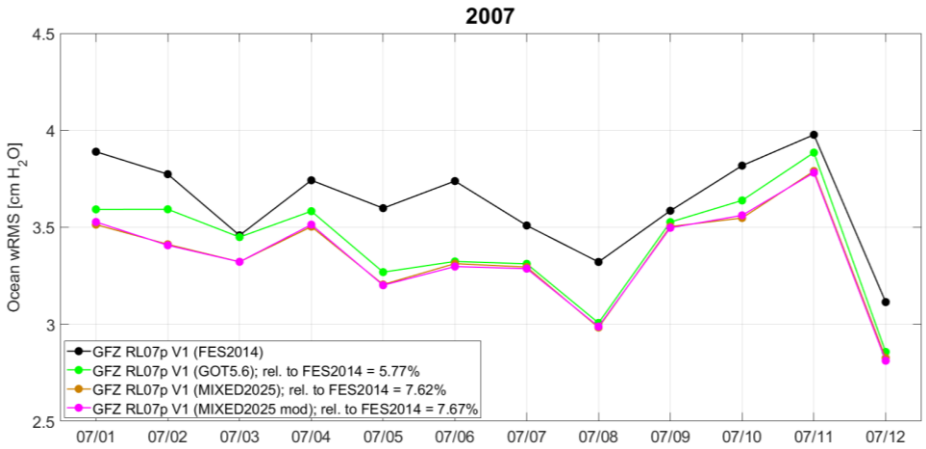
note different scale of color bar

GFZ Helmholtz Centre for Geosciences

Results: 2) Ocean tide model for GFZ RL07

GRACE

Ocean RMS



- Conclusions are consistent with those from the GRACE-FO test year
- MIXED2025 again performs slightly better than GOT5.6
- Further investigations at GFZ revealed that small modifications of MIXED2025 lead to reduced residual variance in the Weddell Sea and off the coast of West Antarctica
  - Tidal constituents d3m1, d3n2, d3l2 and d3m3 are taken from TiME22 instead of GOT5.6 ➔ all degree-3 tides are now from TiME22
- The model denoted here as **MIXED2025 mod** has been chosen for GFZ RL07

Summary

- New unified approach for tidal corrections during orbit and gravity field determination is proposed
  - User-friendly, model-independent, no expert knowledge of ocean tide theory required
  - Paper in preparation, goal is to become part of next IERS conventions
  - Your feedback is welcome!
- Implementation of this new approach in GFZ's EPOS-OC software in view of the GRACE/-FO RL07 reprocessing could already prove its benefits
  - Extended admittance scheme improves gravity field results
  - Ocean tide model comparisons can be performed without extra work needed to implement different new models
- Recommendation to use a mixed model to obtain best gravity field results