New Refined Observations of Climate Change from Spaceborne Gravity Missions

Signatures of degree-3 tidal loading effects in superconducting gravimeter records predicted by data-unconstrained ocean tide modeling

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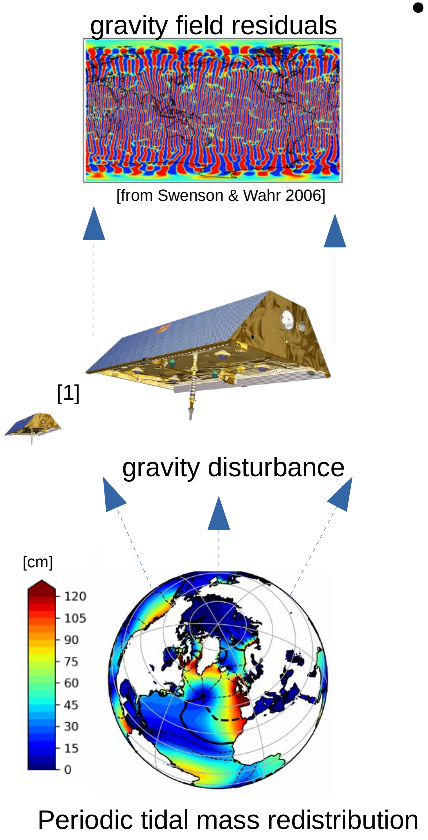
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

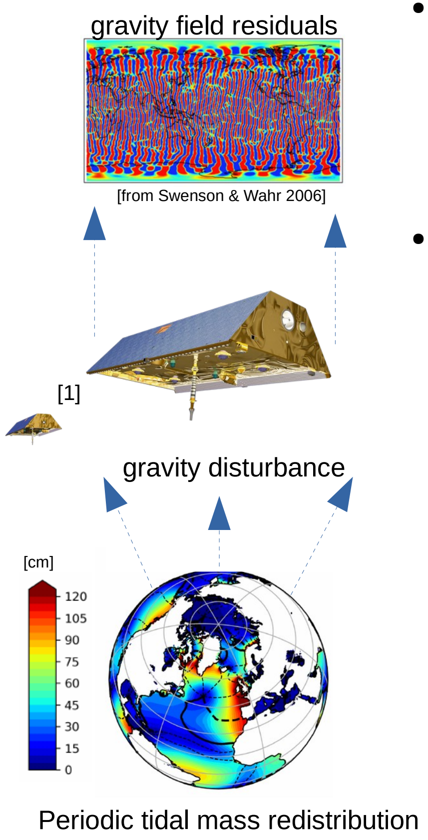
Ocean tide modeling for satellite gravimetry



- Dealiasing of GRACE(-FO) data by application of background models

  → Imperfections induce significant residuals into gravity solutions (Flechtner, 2016)

Ocean tide modeling for satellite gravimetry



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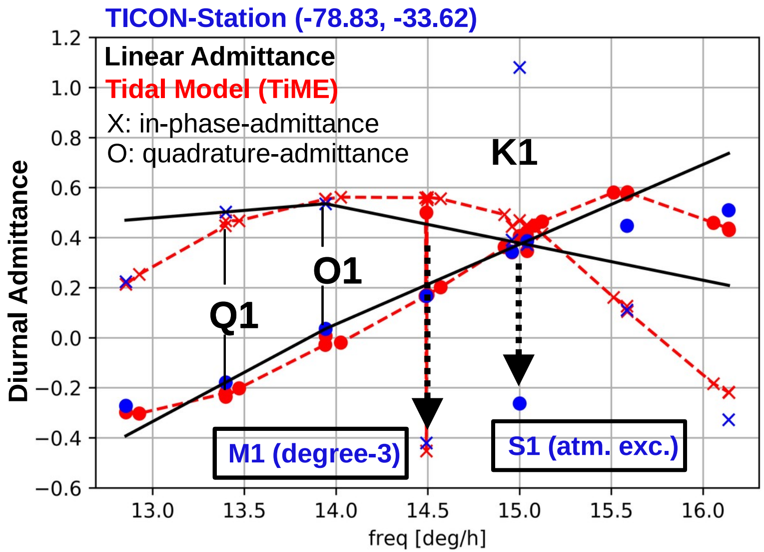
- Ocean tidal dynamics can be decomposed into a set of partial tides

  → Small amplitude tides are usually derived with admittance assumptions



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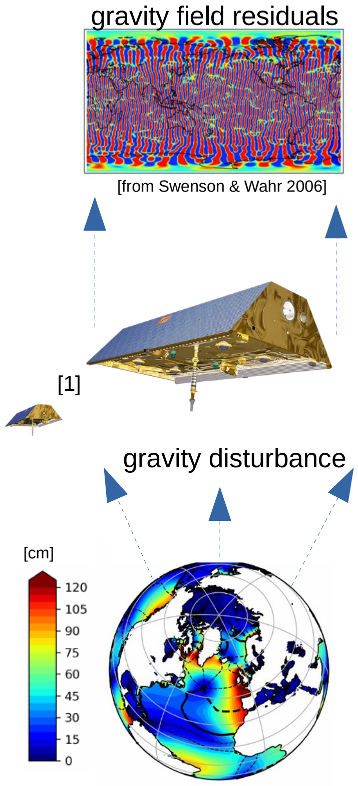

Periodic tidal mass redistribution

- Dealiasing of GRACE(-FO) data by application of background models

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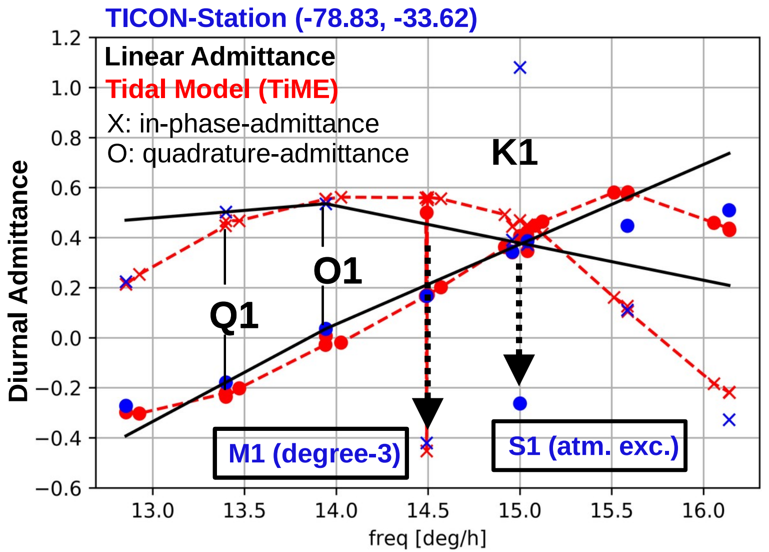
- Ocean tidal dynamics can be decomposed into a set of partial tides

  → Small amplitude tides are usually derived with admittance assumptions

- Admittance assumptions break down for atmospherically excited ocean tides (e.g. S1), and **degree-3 ocean tides**

  → Individual partial tide solutions required



Barotropic Ocean Tide Modeling and Validation

MODELING

VALIDATION

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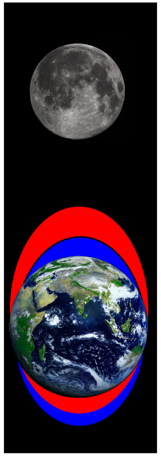
Tide-Raising Forces

The lunar tide-raising potential possesses an asymmetric part described in first order by degree-3 spherical harmonic functions



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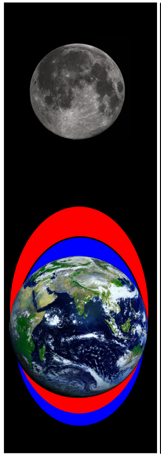
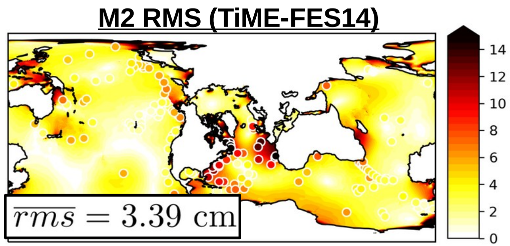


<u>Ocean Tide Model</u>
We employ the ocean tide model TiME (Sulzbach, 2021)



<u>Model characteristics:</u>
- data-unconstrained, finite-differences
- 1/12 ° resolution, **rotated poles**
- energy dissipation: bottom friction, param. eddy-viscosity and **wavedrag**
- Consideration of the non-local effect of Self-attraction and Loading **(SAL)**
- **rtopo2 bathymetry** including cavities below the Antarctic ice-shelf

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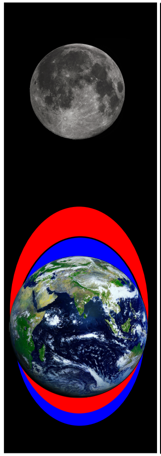

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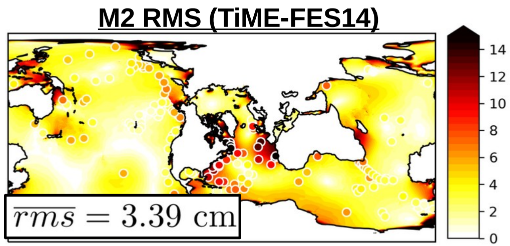

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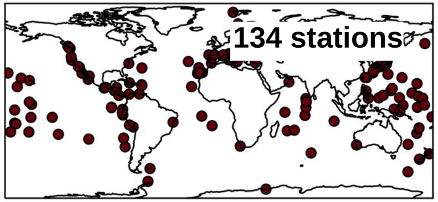
VALIDATION

Validation with TG-data (M. Hart-Davis)

- Tidal analysis of tide gauge data (GESLA) to TICON-dataset (open ocean subset) (Piccioni, 2019)
- TG-constituents represent **point measurements**



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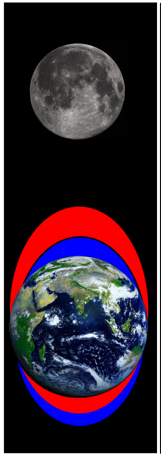

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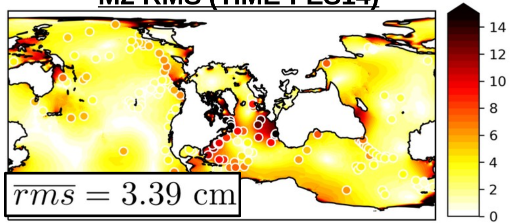

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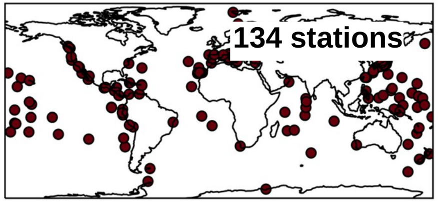

Validation with SG-data (H. Wziontek)
- Tidal analysis of superconducting gravimeter time-series with ETERNA-X (http://ggp.bkg.bund.de/eterna)
- Modeling of surface gravimetric signals with spotl (Agnew, 2012)
- SG-constituents represent a **globally-integrated measurement**

(OSG-030, Wettzell, Germany)

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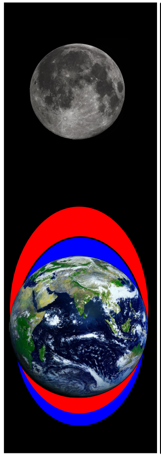

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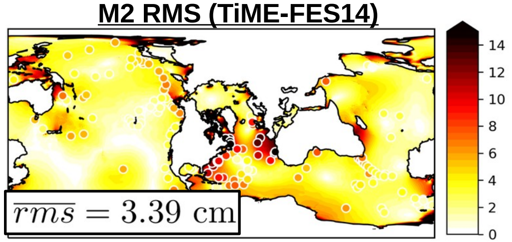

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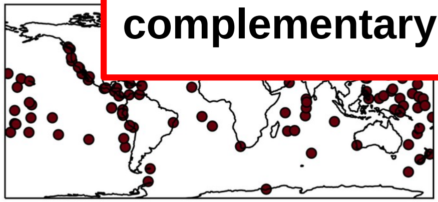

→ SG and TG data represent complementary tidal metrices

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Data-unconstrained Degree-3 Tidal Atlas

- We employ the nomenclature of Ducarme (2012) for labeling partial tides

  → monthly species (**3MO0**), diurnal species (**M1**), semidiurnal species (**3MO2, 3MK2**), terdirunal species (**M3**)

- We employ the **r**oot-**m**ean-**s**quare metric to compare modeled vs. analyzed constituents

$$rms(\zeta_M^\omega) = \sqrt{\frac{1}{2\cdot 134}\sum_{i=1}^{134}|\zeta_M^\omega(\boldsymbol{x}_i) - \zeta_{TG}^\omega(\boldsymbol{x}_i)|^2} \quad rms(g_M^\omega) = \sqrt{\frac{1}{2\cdot 16}\sum_{i=1}^{16}|g_M^\omega(\boldsymbol{x}_i) - g_{SG}^\omega(\boldsymbol{x}_i)|^2}$$

- TiME-solutions correspond closely to recently published studies:

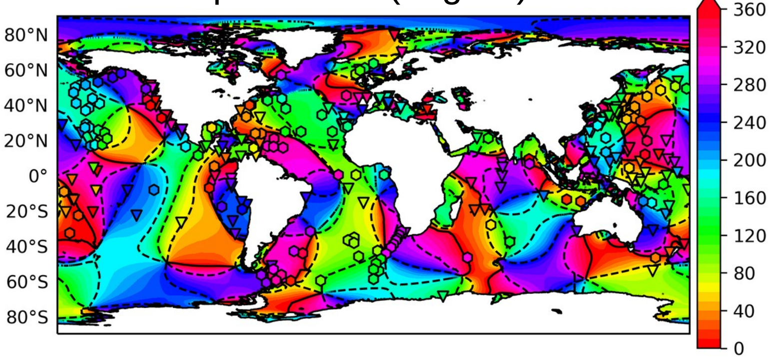
  → Data-unconstrained solution for M1 (Woodworth, 2019)

  → Altimetry data-constrained atlas for M1, 3MO2, 3MK2, M3 (Ray, 2020)

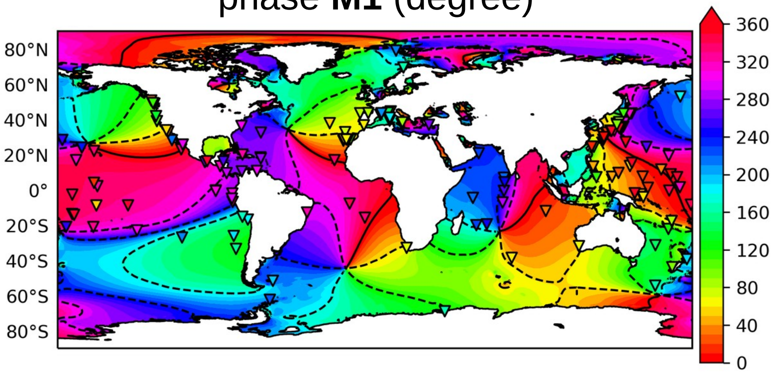
TG-rms is minimized by varying model parameters

Modeled and Analyzed Sea Level Signal

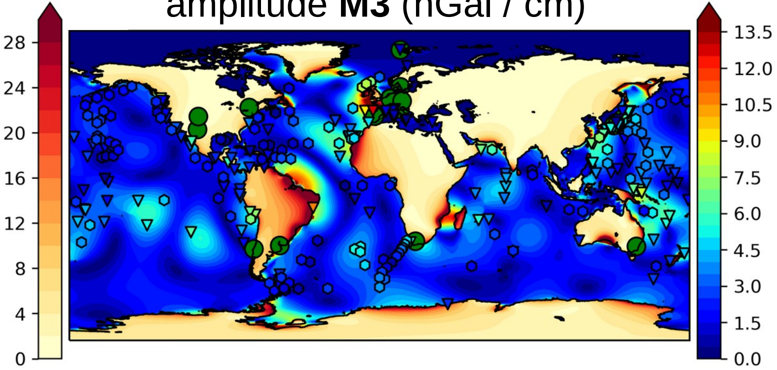
phase **M3** (degree)



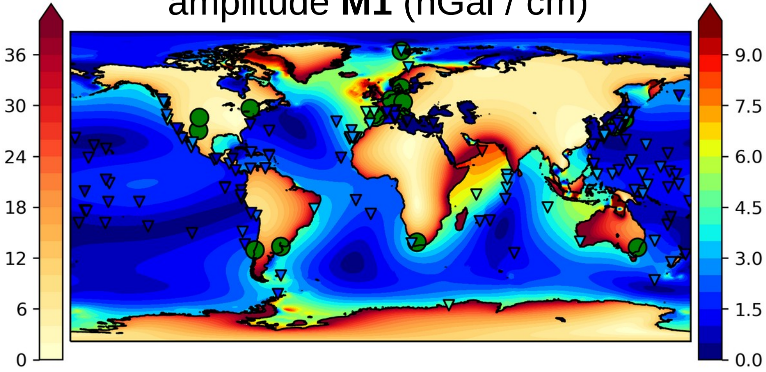
phase **M1** (degree)



amplitude **M3** (nGal / cm)



amplitude **M1** (nGal / cm)



3MO2

0.9 / 2.5 mm

3MK2

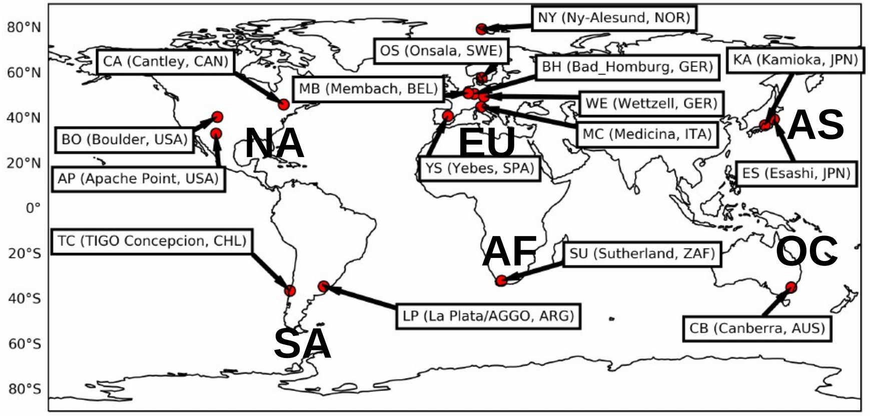
0.9 / 2.0 mm

Mean agreement between **33%** (M1) and **64%** (3MO2)

rms/signal : **M3** **1.3 / 2.9 mm** **M1** **1.0 / 1.5 mm**

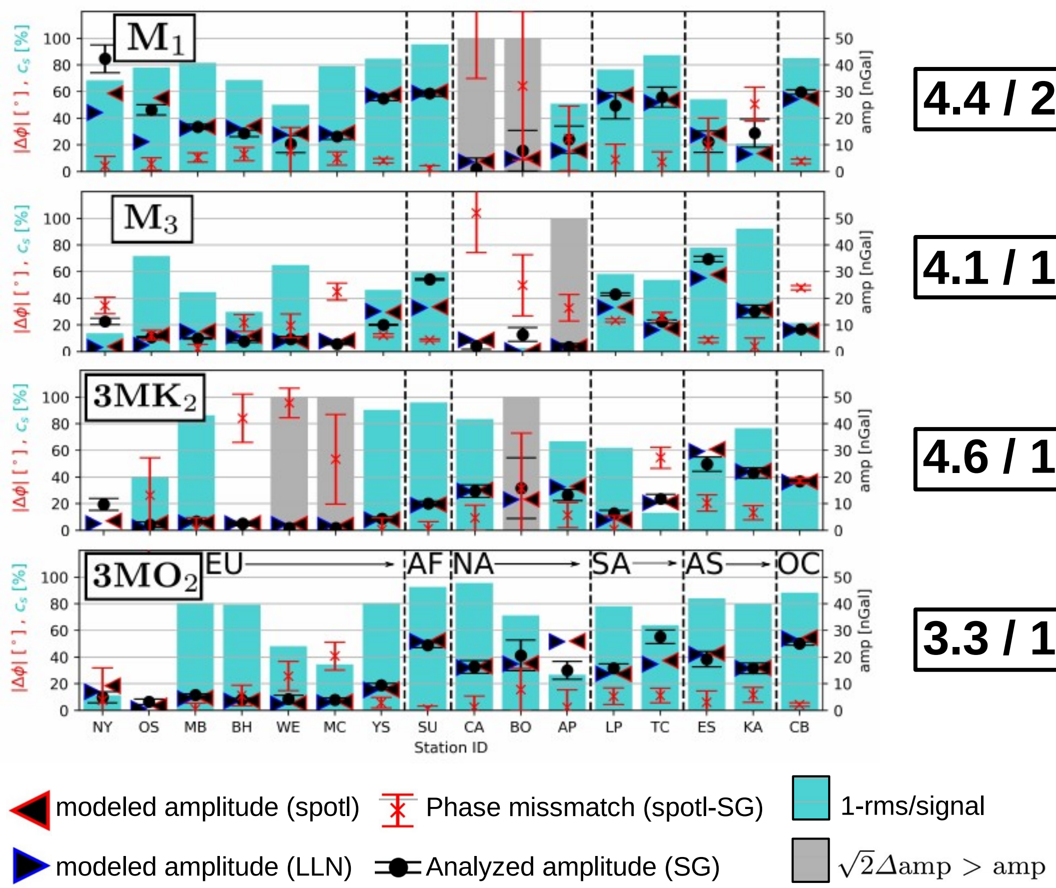
Modeled and Analyzed Gravimetric Signal

Global SG-distribution



→ Global ensemble of 16 SG stations

→ Mean agreement between **63%** (3MK2) and **80%** (M1)



rms/signal [nGal]

4.4 / 21.7
4.1 / 14.1
4.6 / 12.4
3.3 / 15.8

GFZ Helmholtz Centre Potsdam

NEROGRAV New Refined Observations of Climate Change from Spaceborne Gravity Missions

Summary

- First data-unconstrained tidal atlas comprising partial tides of all degree-3 tidal species
- Tidal analysis of SG time series feasible for few nGal degree-3 signals with ETERNA-x
- Rms-metric for tide gauge and SG ensemble shows agreement over 50%
  → Modeled and analyzed tidal signals correspond to each other
- The mean gravimetric signal is highest for diurnal and long-period tides (M1, 3MO0), while the respective tide gauge signals are small
  → SG data is especially useful to validate small-amplitude tides with relatively long periods

References

D. C. Agnew.
NLOADF: A program for computing ocean-tide loading.
J. Geophys. Res., 102:5109–5110, 1997.

D. C. Agnew.
SPOTL : Some Programs for Ocean- Tide Loading.
Scripps Inst. Oceanogr. Tech. Rep., 2012.

B. Ducarme.
Determination of the main Lunar waves generated by the third degree tidal potential and validity of the corresponding body tides models.
J. Geod., 86(1):65–75, 2012.

F. Flechtner, K. H. Neumayer, C. Dahle, H. Dobslaw, E. Fagiolini, J. C. Raimondo, and A. Güntner.
What Can be Expected from the GRACE-FO Laser Ranging Interferometer for Earth Science Applications?
Surv. Geophys., 37(2):453–470, 2016.

G. Piccioni, D. Dettmering, W. Bosch, and F. Seitz.
TICON: TIdal CONstants based on GESLA sea-level records from globally located tide gauges.
Geosci. Data J., 6(2):97–104, 2019.

R. D. Ray.
First global observations of third-degree ocean tides.
Sci. Adv., 6(48):1–8, 2020.

K. Schüller.
”Program System ETERNA-x et34-x-v80-* for Earth and Ocean Tides Analysis and Prediction, Documentation Manual 01: Theory”.
Technical report, Institution:, 2020.

R. Sulzbach, H. Dobslaw, and M. Thomas.
High-Resolution Numerical Modelling of Barotropic Global Ocean Tides for Satellite Gravimetry.
J. Geophys. Res. Ocean., pages 1–21, 2021.

S. Swenson and J. Wahr.
Post-processing removal of correlated errors in GRACE data.
Geophys. Res. Lett., 33(8):1–4, 2006.

L. P. Woodworth.
The global distribution of the M1 ocean tide.
Ocean Sci., 15(2):341–442, 2019.