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

Roman Sulzbach¹,²*, Hartmut Wziontek³, Michael Hart-Davis⁴, Henryk Dobslaw¹ and Maik Thomas¹,²

¹Deutsches Geoforschungszentrum (GFZ), Potsdam
²Institut für Meteorologie, Freie Universität Berlin (FUB), Berlin
³Bundesamt für kartographie und Geodäsie (BKG), Leipzig, Germany
⁴Deutsches Geodätisches Forschungsinstitut der Technischen Universität München, München (DGFI-TUM)
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

- Dealiasing of GRACE(-FO) data by application of background models
  → Imperfections induce significant residuals into gravity solutions (Flechtner, 2016)

- Ocean tidal dynamics can be decomposed into a set of partial tides
  → Small amplitude tides are usually derived with admittance assumptions
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 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

Periodic tidal mass redistribution

gravity field residuals

[from Swenson & Wahr 2006]

gravity disturbance

TICON-Station (-78.83, -33.62)

Linear Admittance
Tidal Model (TiME)

M1 (degree-3)

D1r

A
d
m
i
t
a
c
ce
S1 (atm. exc.)

Q1

O1

K1

X: in-phase-admittance
O: quadrature-admittance

13.0 13.5 14.0 14.5 15.0 15.5 16.0

TICON-Station (-78.83, -33.62)
Linear Admittance
Tidal Model (TiME)
X: in-phase-admittance
O: quadrature-admittance

GFZ Helmholtz Centre Potsdam

GSTM-2021, 20.10.2021, Roman Sulzbach, 4
Barotropic Ocean Tide Modeling and Validation
Tide-Raising Forces
The lunar tide-raising potential possesses an asymmetric part described in first order by degree-3 spherical harmonic functions.
**Tide-Raising Forces**

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

**Ocean Tide Model**

We employ the ocean tide model TiME (Sulzbach, 2021)

Model characteristics:
- 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)
- rtopo bathymetry including cavities below the Antarctic ice-shelf
Barotropic Ocean Tide Modeling and Validation

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

Ocean Tide Model
We employ the ocean tide model TiME (Sulzbach, 2021)

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

Model characteristics:
- 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-atraction and Loading (SAL)
- rtopo2 bathymetry including cavities below the Antarctic ice-shelf
Barotropic Ocean Tide Modeling and Validation

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

**Ocean Tide Model**
We employ the ocean tide model TiME (Sulzbach, 2021)

- 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

- 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

**Model characteristics:**
- 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

- M2 RMS (TIME-FES14)
  - rms = 3.39 cm

Model characteristics:
- 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
Barotropic Ocean Tide Modeling and Validation

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

**Ocean Tide Model**
We employ the ocean tide model TiME (Sulzbach, 2021)

- **M2 RMS** (TIME-FES14)
  - $rms = 3.39$ cm

**Model characteristics:**
- 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

**Validation with TG-data (M. Hart-Davis)**
- Tidal analysis of tide gauge data (GESLA) to TICON-dataset (open data) (Piccioni, 2019)
- TG-constituents represent point measurements

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

→ **SG and TG data represent complementary tidal metrics**

GSTM-2021, 20.10.2021, Roman Sulzbach, 10
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 root-mean-square metric to compare modeled vs. analyzed constituents:

\[
\text{rms}(\zeta_M) = \sqrt{\frac{1}{2 \cdot 134} \sum_{i=1}^{134} |\zeta_M(x_i) - \zeta_{TG}(x_i)|^2} \quad \text{rms}(g_M^o) = \sqrt{\frac{1}{2 \cdot 16} \sum_{i=1}^{16} |g_M^o(x_i) - g_{SG}^o(x_i)|^2}
\]

- 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 $M_1$ (degree)

Phase $M_3$ (degree)

Amplitude $M_1$ (nGal/cm)

Amplitude $M_3$ (nGal/cm)

rms/signal:

$M_3 \ 1.3 / 2.9 \ mm$

$M_1 \ 1.0 / 1.5 \ mm$

3MO2

0.9 / 2.5 mm

3MK2

0.9 / 2.0 mm

Mean agreement between 33% ($M_1$) and 64% (3MO2)
Modeled and Analyzed Gravitometric Signal

Global SG-distribution

- Global ensemble of 16 SG stations
- Mean agreement between 63% (3MK2) and 80% (M1)

<table>
<thead>
<tr>
<th>rms/signal [nGal]</th>
<th>M1</th>
<th>M3</th>
<th>3MK2</th>
<th>3MO2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4 / 21.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1 / 14.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.6 / 12.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3 / 15.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1-rms/signal

modeled amplitude (spotl)

Phase mismatch (spotl-SG)

modeled amplitude (LLN)

Analyzed amplitude (SG)

$\sqrt{2}\Delta$amp > amp
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


