The magnetic signatures of oceanic tides in satellite data
A virtual-observatory approach

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Virtual observatories

- a robust procedure for estimating high-resolution time series of the secular variation of the core field
- introduced by Mandaea & Olsen (2006), later reused by Olsen, Beggan, Whaler,...
  + local method with local error estimates
  + usually does not imply any regularization in time (unlike global field models)
  - problem with external field contamination (ideally should average to zero)
  - more strict data selection criteria → strong reduction of data dimension for local inversion

after C. Finlay
Virtual observatories and tides
Local Laplacian potential field: tidal parameterization

- local quadratic/cubic parameterization in Cartesian coordinates

\[ V(x, y, z; t) = \sum_{a+b+c \leq l} C_{abc}(t) x^a y^b z^c \]

- \( k = 1, \ldots, K \): individual tidal constituents (e.g., \( M_2, N_2, O_1 \))

\[ C_{abc}(t) = \text{Re} \left\{ \sum_{k=1}^{K} f_k(t) \hat{c}_{abc,k} \exp [i(\omega_k(t - t_0) + V_{0,k}(t_0) + u_k(t))] \right\} \]

where \( \hat{c}_{abc,k} \in \mathbb{C} \)

- tidal parameters, available from TPXO subroutines (Egbert & Erofeeva 2002)
  - \( \omega_k \): angular frequency
  - \( f_k(t) \): amplitude modulation (seasonal)
  - \( u_k(t) \): phase modulation
  - \( V_{0,k}(t_0) \): Greenwich phase related to \( t_0 = 1992.0 \)

- number of free complex parameters \( \hat{c}_{abc,k} \): 8K/15K
1. select satellite data by quietness criteria
2. subtract a-priori models of main and external fields
3. choose a virtual observatory, a search radius (∼ 500 km) and all times
4. select all residua within the search radius
5. rotate the residua to a local Cartesian coordinate system
6. fit local time-dependent Laplacian potential field with a-priori tidal parameters by Iterative Reweighted Least-Squares with Huber weights
7. repeat from 3 for next VO
Virtual observatories and tides
VO Algorithm for tidal signals

1. select satellite data by quietness criteria
   - $K_p < 3$
   - $|\frac{dRC}{dt}| < 3 \text{ nT/hr}$
   - $E_m \leq 0.8 \text{ mV/m}$
   - $B_{z,\text{IMF}} > 0 \text{ nT}$
   - $|B_{y,\text{IMF}}| < 10 \text{ nT}$
   - Sun at least $10^\circ$ below horizon

2. subtract a-priori models of main and external fields

3. choose a virtual observatory, a search radius ($\approx 500 \text{ km}$) and all times

4. select all residua within the search radius

5. rotate the residua to a local Cartesian coordinate system

6. fit local time-dependent Laplacian potential field with a-priori tidal parameters by Iterative Reweighted Least-Squares with Huber weights

7. repeat from 3 for next VO
Virtual observatories and tides

VO Algorithm for tidal signals

1. select satellite data by quietness criteria
2. subtract a-priori models of main and external fields
   ▶ core field and lithosphere (CHAOS-6)
   ▶ magnetospheric external field (CHAOS external model)
   ▶ ionospheric external and induced field (CIY4 model)
3. choose a virtual observatory, a search radius (≈ 500 km) and all times
4. select all residua within the search radius
5. rotate the residua to a local Cartesian coordinate system
6. fit local time-dependent Laplacian potential field with a-priori tidal parameters by Iterative Reweighted Least-Squares with Huber weights
7. repeat from 3 for next VO
Virtual observatories and tides

Example of data and phase coverage

left: spatial coverage around a VO in the Northern Pacific; blue circles mark distance from the VO with 200 km steps

right: coverage of the phase of individual tides for 600 km distance
Numerical modelling

- elmFD: frequency-domain spherical harmonic-finite element solver
- zero external forcing, preconditioned BiCGSTAB(2), OpenMP (Velímský et al. 2018)
- $j_{\max} = 480$, $K_{3D} = 101$
- 1-D mantle conductivity profile (Grayver et al. 2017)
- 3-D ocean conductivity based on collocated temperature and salinity measurements (World Ocean Atlas, Tyler et al. 2017)
- ocean-bottom sediments (a-priori assigned values and maps of thicknesses, Everett et al. 2003)
- TPXO9-atlas ocean flows for $M_2$, $N_2$, $O_1$
VO analysis setup for Swarm A and C

Parameter study for $M_2$, $N_2$, $O_1$

- number of VOs in regular grid ($N_\varphi \times N_\vartheta$)
- search radius $d$
- fields (A,C): $B^A_i$, $B^C_i$
- NS+EW differences (A-C,A+C)

NS along-track differences and sums on both satellites: $\frac{B^A_{i+1} - B^A_i}{2}$,
$\frac{B^A_{i+1} + B^A_i}{2}$, $\frac{B^C_{i+1} - B^C_i}{2}$, $\frac{B^C_{i+1} + B^C_i}{2}$

EW cross-track differences and sums $\frac{B^A_i - B^C_i}{2}$, $\frac{B^A_i + B^C_i}{2}$
Selected results

$M_2$

Swarm A and Swarm C fields

036x018,0500 km, A, C

Grayver & Olsen 2019 (SH28)

Forward model (SH480)
Selected results

\(M_2\)

Swarm A and Swarm C fields

036x018, 1000 km, A, C

Grayver & Olsen 2019 (SH28)

Forward model (SH480)
Selected results

$M_2$

Swarm A and Swarm C fields

036°018, 2000 km, A, C

Grayver & Olsen 2019 (SH28)

Forward model (SH480)

Velímský et al. (CUP, DTU)

Tides in virtual observatories

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Selected results

\( M_2 \)

Swarm A and Swarm C fields

072x036, 1000 km, A, C

Grayver & Olsen 2019 (SH28)

Forward model (SH480)

Velímský et al. (CUP, DTU)

Tides in virtual observatories
Selected results

$M_2$

Swarm A and C NS and EW sums and differences

036x018,0500 km, A+C, A−C

Grayver & Olsen 2019 (SH28)

Forward model (SH480)
Selected results

$M_2$

Swarm A and C NS and EW sums and differences

036x018,1000 km, A+C, A−C

Grayver & Olsen 2019 (SH28)

Forward model (SH480)
Selected results

$M_2$

Swarm A and C NS and EW sums and differences

036x018,2000 km, A+C, A−C

Grayver & Olsen 2019 (SH28)

Forward model (SH480)

Velímský et al. (CUP, DTU)
Selected results

\( M_2 \)

Swarm A and C NS and EW sums and differences

072x036,1000 km, A+C, A−C

Grayver & Olsen 2019 (SH28)

Forward model (SH480)

Velímský et al. (CUP, DTU)

Tides in virtual observatories

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Selected results

\[ N_2 \]

Swarm A and C NS and EW sums and differences

036x018,2000 km, A+C, A−C

Grayver & Olsen 2019 (SH12)

Forward model (SH480)

Velímský et al. (CUP, DTU)

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Comparison of power spectra for $M_2$

Selected results

Comparison of power spectra for $M_2$

Selected results

Comparison of power spectra for $M_2$

Selected results

Comparison of power spectra for $M_2$
Conclusions

\[ \text{M}_2 \text{ successfully recovered from Swarm A,C data by VO approach} \]

\begin{itemize}
  \item significant dependence on the choice of search radius \(d\) (smoother solution with suppressed higher harmonics for large \(d\))
  \item use of NS and EW differences does not introduce any particular advantage
  \item alternative corrections for external field to be exploited
\end{itemize}

\[ \text{N}_2 \text{ poorly recovered} \]

\[ \text{O}_1 \text{ not recovered} \]