The magnetic signatures of oceanic tides in satellite data

A virtual-observatory approach

Jakub Velímský
Magnus D. Hammer, and Christopher C. Finlay

DTU Space
National Space Institute

Dept. of Geophysics
Faculty of Mathematics and Physics
Charles University
Prague

DTU Space
National Space Institute
Kgs. Lyngby

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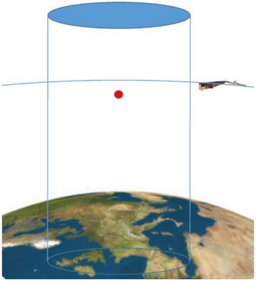
Virtual observatories

- a robust procedure for estimating high-resolution time series of the secular variation of the core field
- introduced by Mandea & 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

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

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

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

  where $\hat{c}_{abc,k} \in \mathbb{C}$
- tidal parameters, available from TPXO subroutines (Egbert & Erofeeva 2002)

ω_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

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
3. choose a virtual observatory, a search radius ($\approx 500\,\mathrm{km}$) 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
   - $K_p < 3$
   - $\left|\frac{\mathrm{d}RC}{\mathrm{d}t}\right| < 3\,{}^{\mathrm{nT}}/_{\mathrm{hr}}$
   - $E_m \leqslant 0.8\,{}^{\mathrm{mV}}/_{\mathrm{m}}$
   - $B_z^{\mathrm{IMF}} > 0\,\mathrm{nT}$
   - $\left|B_y^{\mathrm{IMF}}\right| < 10\,\mathrm{nT}$
   - Sun at least 10° below horizon
2. subtract a-priori models of main and external fields
3. choose a virtual observatory, a search radius ($\approx$ 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
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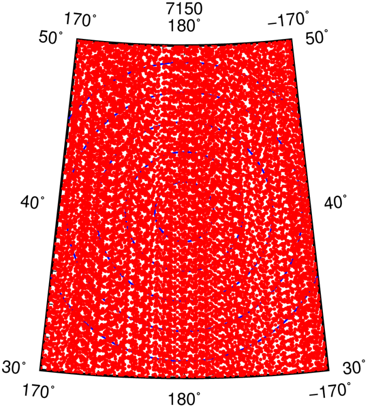
Virtual observatories and tides

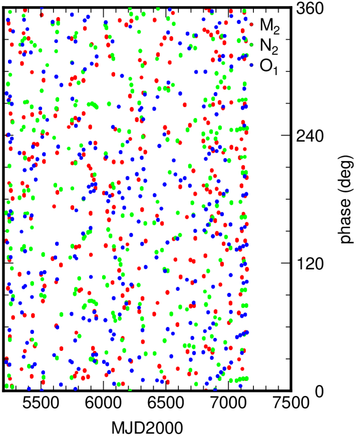
VO Algorithm for tidal signals

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 ($\approx 500\,$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

- elmgFD: 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): $\boldsymbol{B}_i^{\mathrm{A}}$, $\boldsymbol{B}_i^{\mathrm{C}}$
- NS+EW differences (A-C,A+C)

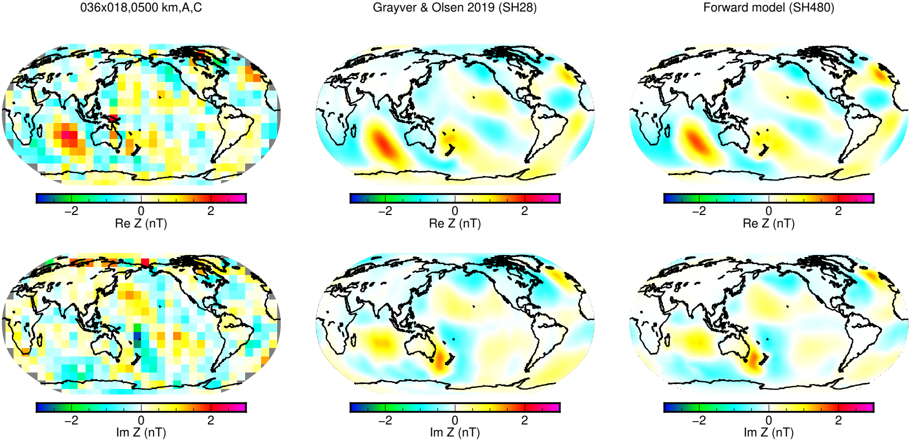
NS along-track differences and sums on both satellites: $\frac{\boldsymbol{B}_{i+1}^{\mathrm{A}}-\boldsymbol{B}_i^{\mathrm{A}}}{2}$, $\frac{\boldsymbol{B}_{i+1}^{\mathrm{A}}+\boldsymbol{B}_i^{\mathrm{A}}}{2}$, $\frac{\boldsymbol{B}_{i+1}^{\mathrm{C}}-\boldsymbol{B}_i^{\mathrm{C}}}{2}$, $\frac{\boldsymbol{B}_{i+1}^{\mathrm{C}}+\boldsymbol{B}_i^{\mathrm{C}}}{2}$

EW cross-track differences and sums $\frac{\boldsymbol{B}_i^{\mathrm{A}}-\boldsymbol{B}_i^{\mathrm{C}}}{2}$, $\frac{\boldsymbol{B}_i^{\mathrm{A}}+\boldsymbol{B}_i^{\mathrm{C}}}{2}$

Selected results

M_2

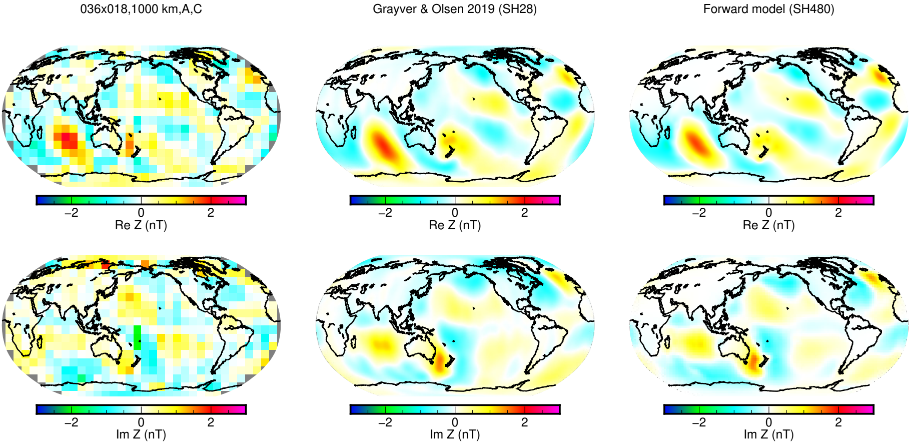
Swarm A and Swarm C fields



Selected results

M_2

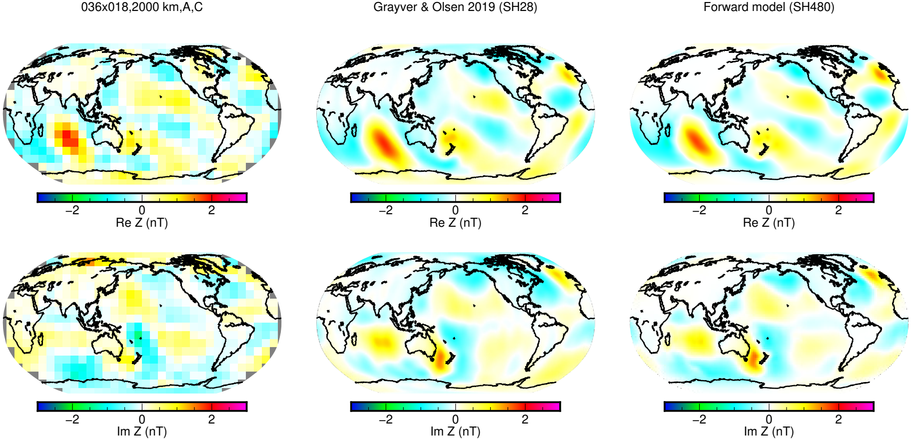
Swarm A and Swarm C fields



Selected results

M_2

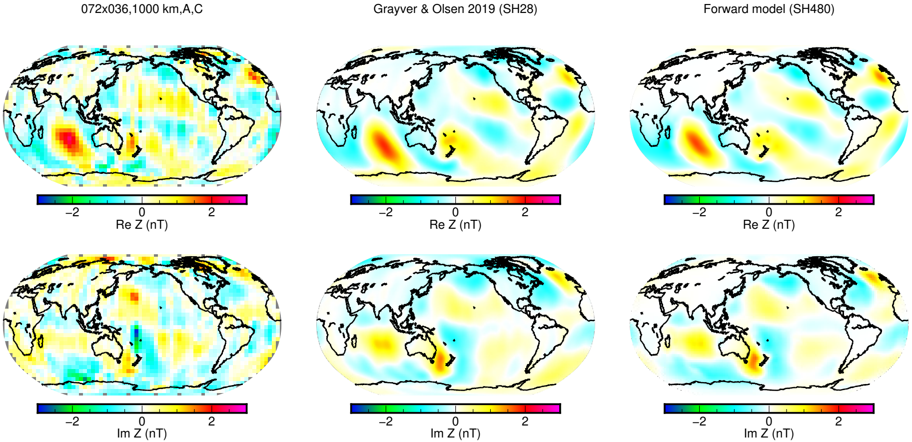
Swarm A and Swarm C fields



Selected results

M_2

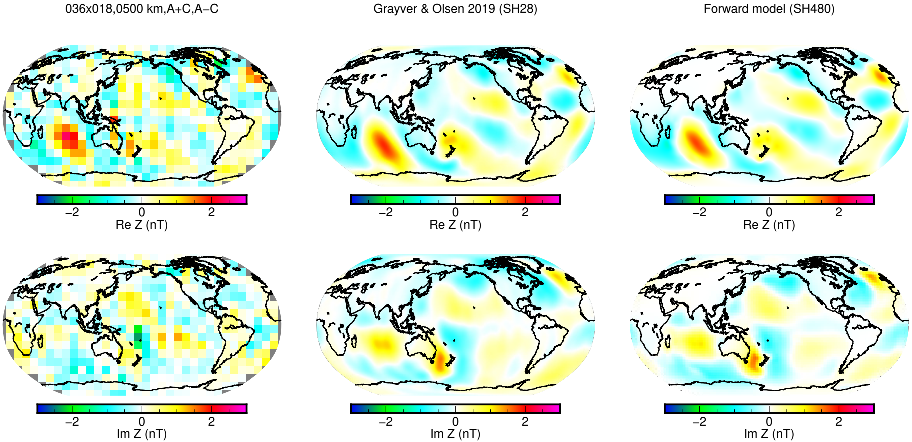
Swarm A and Swarm C fields



Selected results

M_2

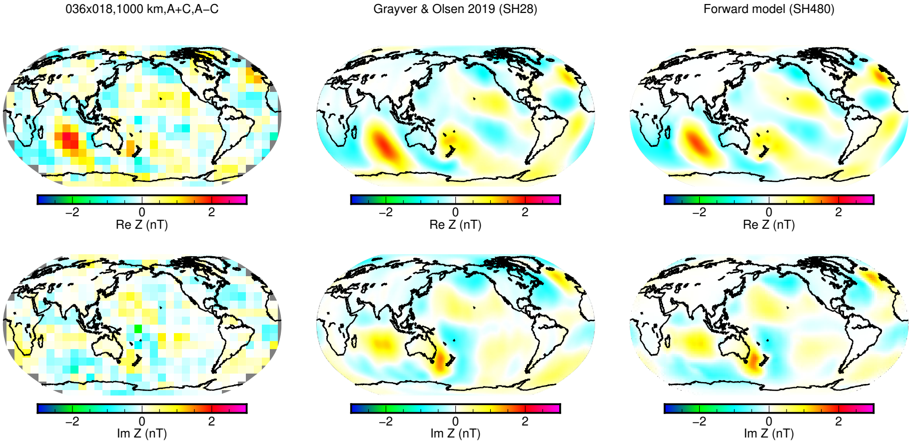
Swarm A and C NS and EW sums and differences



Selected results

M_2

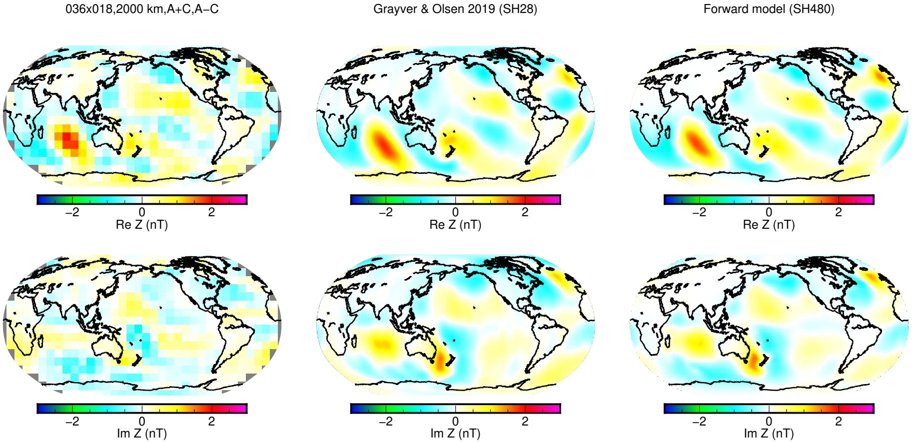
Swarm A and C NS and EW sums and differences



Selected results

M_2

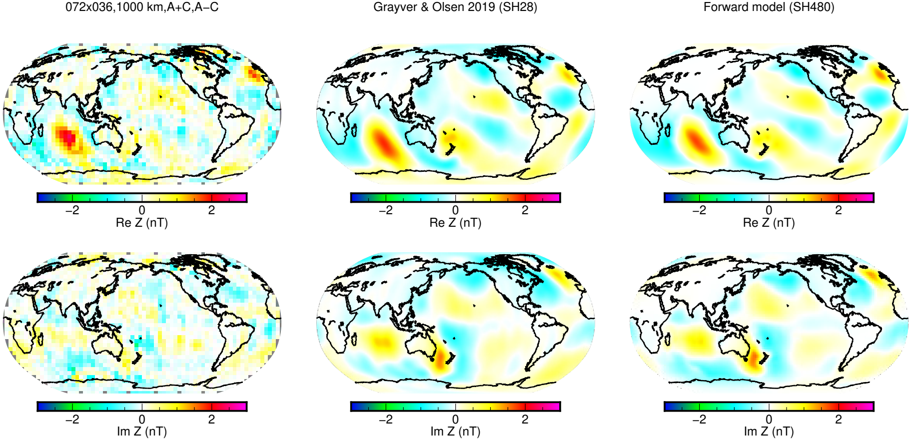
Swarm A and C NS and EW sums and differences



Selected results

M_2

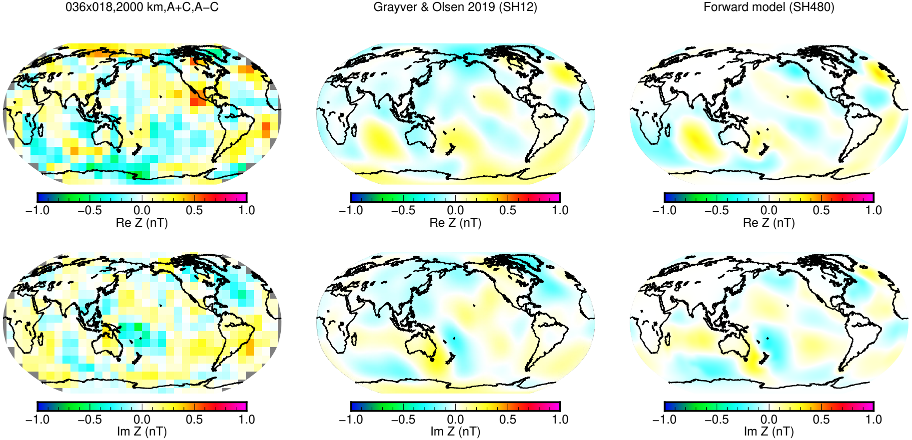
Swarm A and C NS and EW sums and differences



Selected results

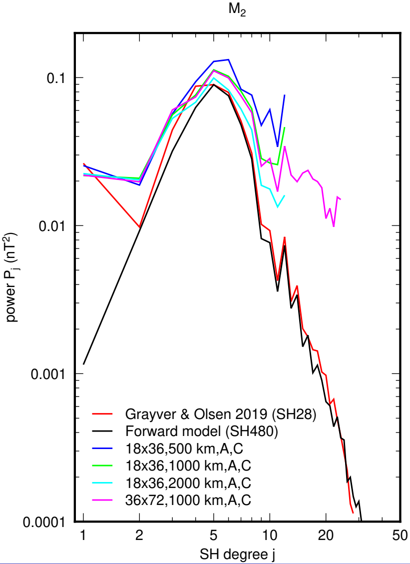
N_2

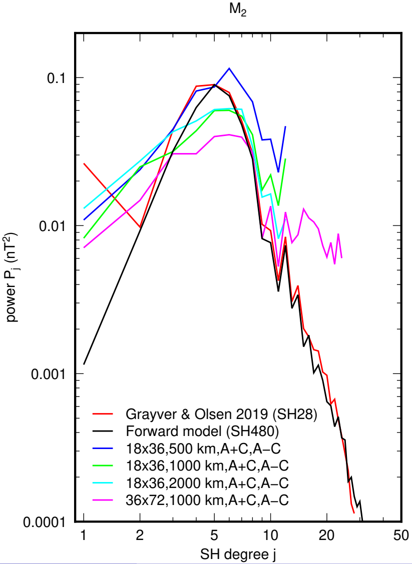
Swarm A and C NS and EW sums and differences



Selected results

Comparison of power spectra for M_2





Conclusions

M_2 successfully recovered from Swarm A,C data by VO approach

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

N_2 poorly recovered

O_1 not recovered