NEROGRAV
New Refined Observations of Climate Change from Spaceborne Gravity Missions

The research unit NEROGRAV: first results on stochastic modeling for gravity field determination with real GRACE and GRACE-FO data

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The Research Unit NEROGRAV

- DFG research unit (RU) started May 2019 (now half-time of 1st phase) with 5 partners (TU Berlin, GFZ, University Bonn, TU Munich, Freie Universität Berlin)
- Central hypothesis:

  only by improving and better understanding of sensor data, background models, and processing strategies, the resolution, accuracy, and long-term consistency of mass transport series from satellite gravimetry can be significantly increased.

- Besides the individual projects (IPs) focusing on background models and validation, IP4 and IP5 work on parameterization and stochastic modeling for GRACE and GRACE-FO gravity field determination

Content of this presentation

1st part on **IP4** (TUB and TUM, OSTPAG: optimized space-time parameterization for GRACE and GRACE-FO data analysis):

- Instrument performance and stochastic modeling for GRACE/GRACE-FO ACC, KBR and LRI data → a priori models for the noise spectra (in terms of PSDs) for different time periods
- Application of different KRR (no LRI yet) weighting schemes on GFZ RL06 GRACE/GRACE-FO monthly solutions (2007/11, 2014/11, and 2019/11)

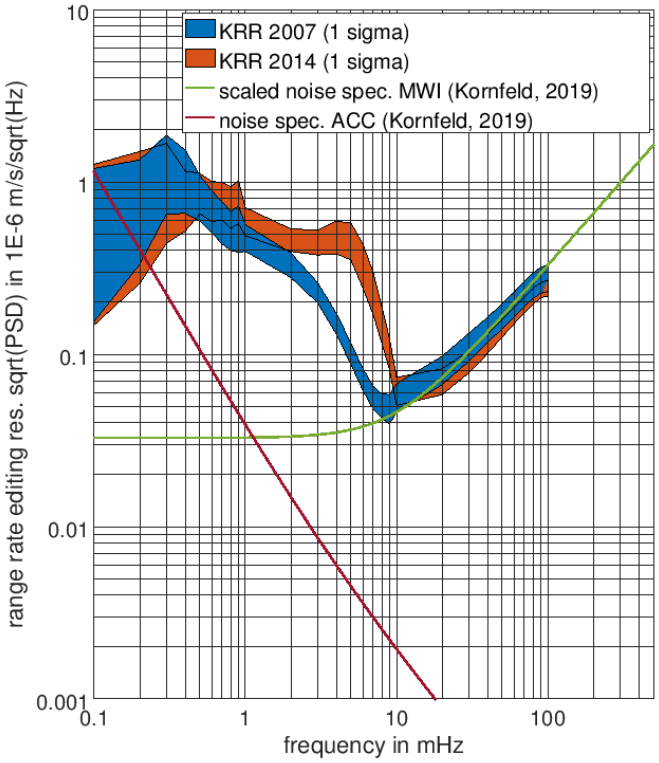
2nd part on **IP5** (GFZ, ISTORE: improved stochastic modeling in GRACE/GRACE-FO real data processing):

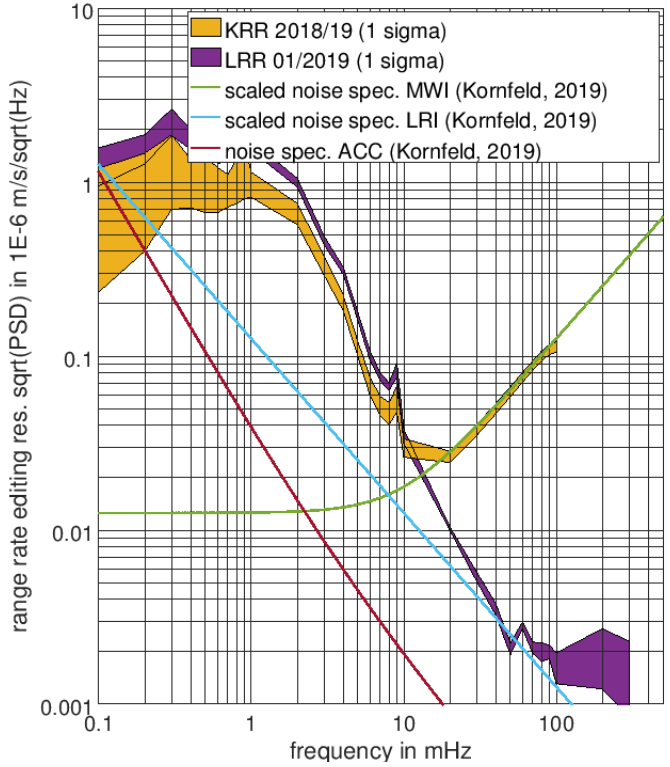
- Simulating the stochastic behaviour of background models (ocean tides and AOD1B product) using Monte-Carlo method

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Separate analyses of ACC and MWI/LRI observations

- GRACE ACC residual analysis for 2007 and 2014 results in two mean PSD noise models for the ACC data (TUM work package)
- GRACE (left) and GRACE-FO (right) KBR/LRI residual analysis results in initial analytical noise models (TUB work package)

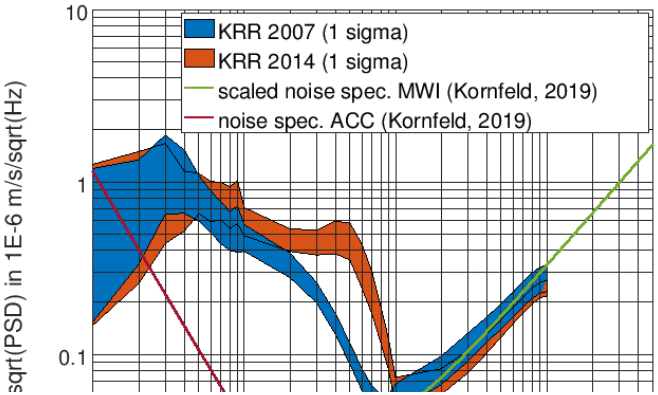


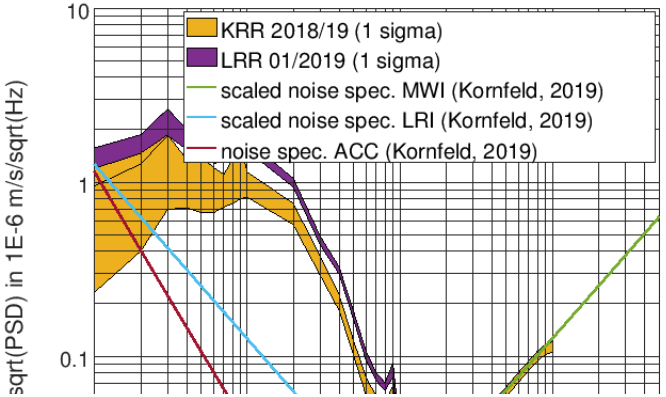


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$$\delta_{\mathrm{GRACE-KRR}} = 0.5 \cdot 2\pi f \cdot \sqrt{1 + (10\ \mathrm{mHz}/f)^2}\ \ \mu\mathrm{m/s}\sqrt{\mathrm{Hz}}$$

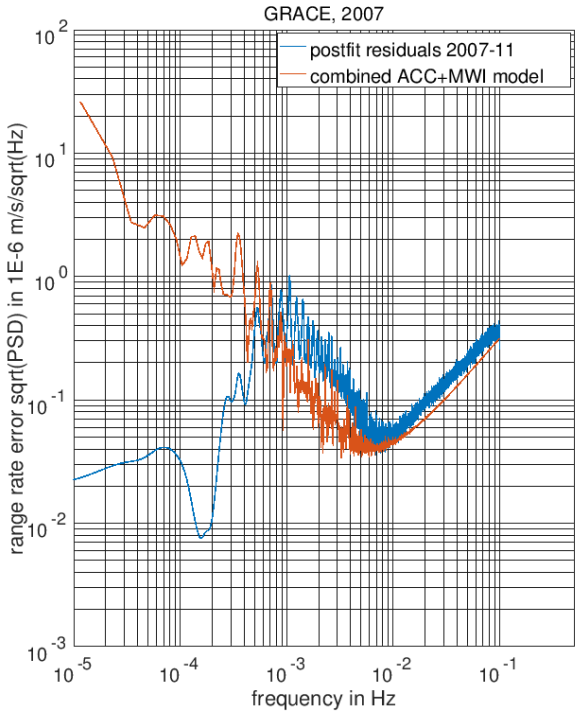
$$\delta_{\mathrm{GRACE-FO-KRR}} = 0.2 \cdot 2\pi f \cdot \sqrt{1 + (10\ \mathrm{mHz}/f)^2}\ \ \mu\mathrm{m/s}\sqrt{\mathrm{Hz}}$$

$$\delta_{\mathrm{GRACE-FO-LRR}} = 0.02 \cdot 2\pi / f\ \ \mathrm{nm/s}\sqrt{\mathrm{Hz}}$$

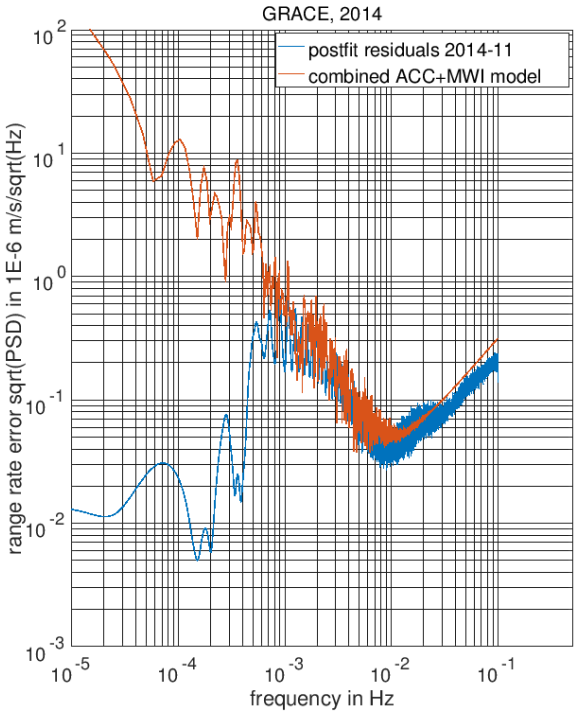
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Combined GRACE/GRACE-FO ACC+KBR noise models for range rate observations (GRACE-FO ACC noise assumed to be the same as for GRACE in 2014)

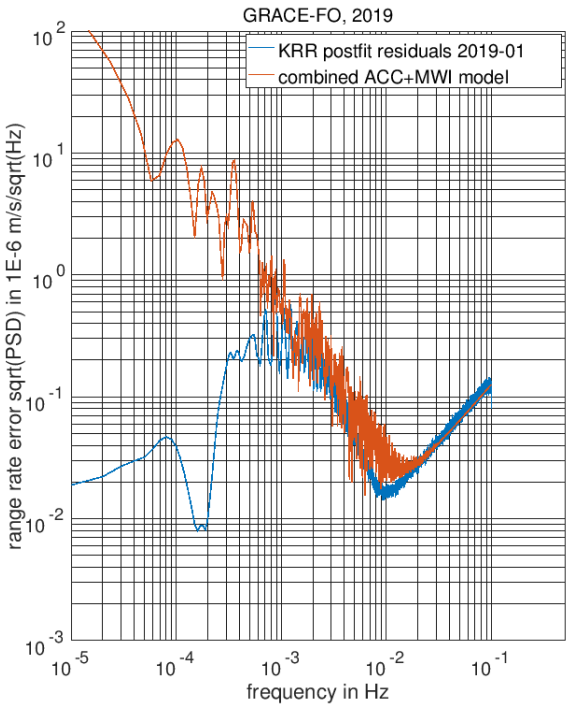
2007



2014



2019

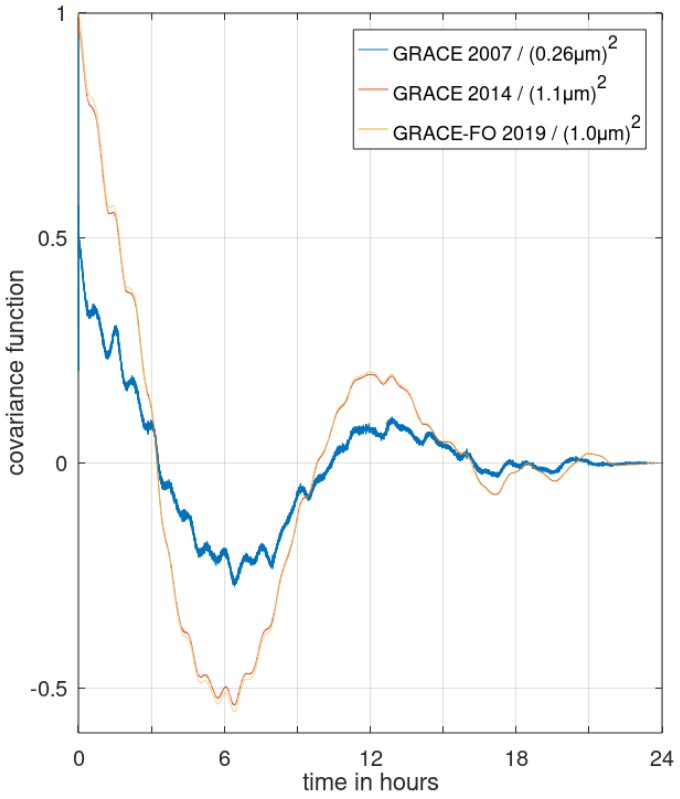


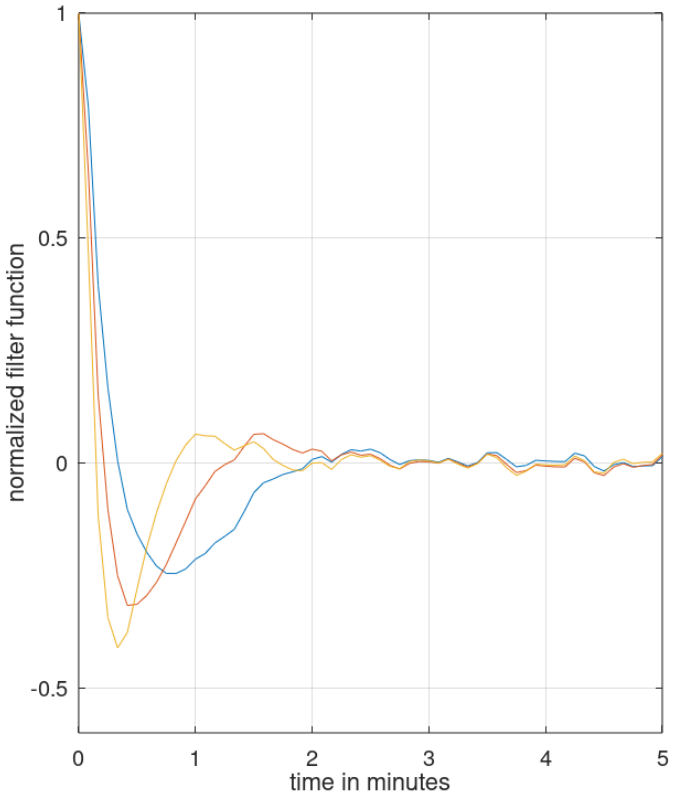
[compared with GFZ RL06 postfit residual PSDs]

1. IP4: filter matrix from covariance function

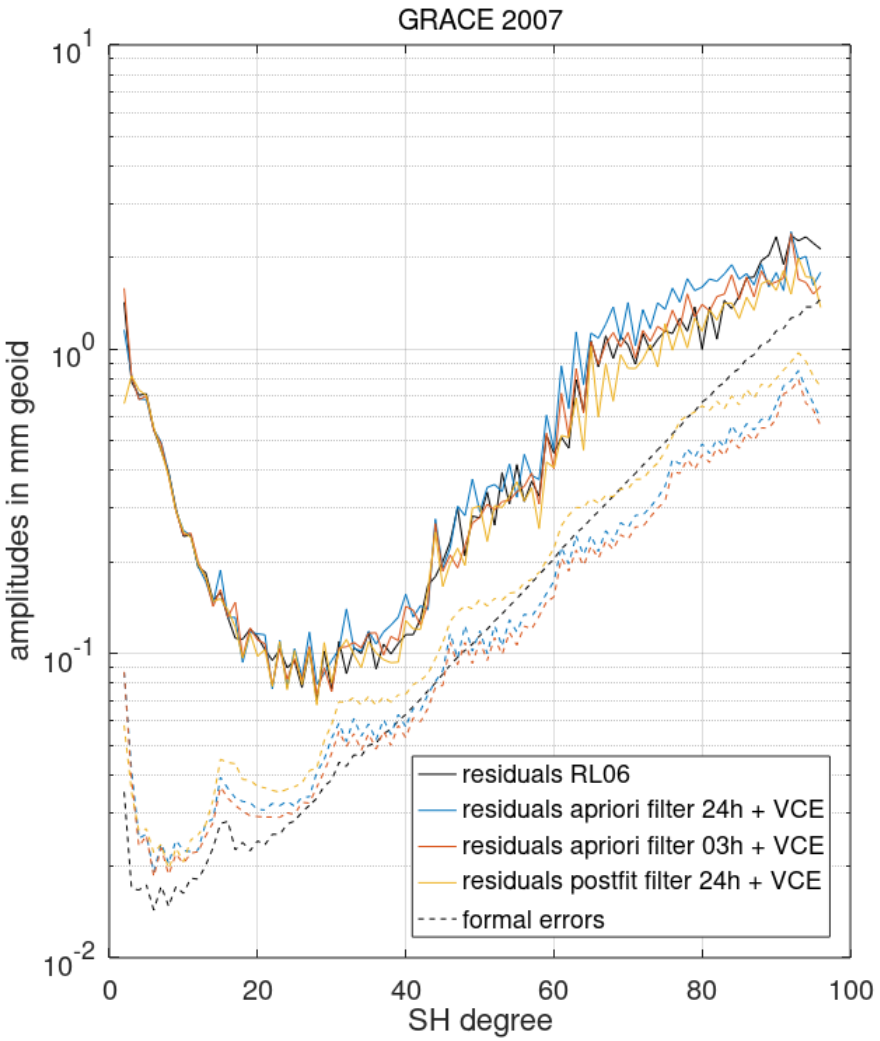
Approach from noise PSDs to weighting matrices

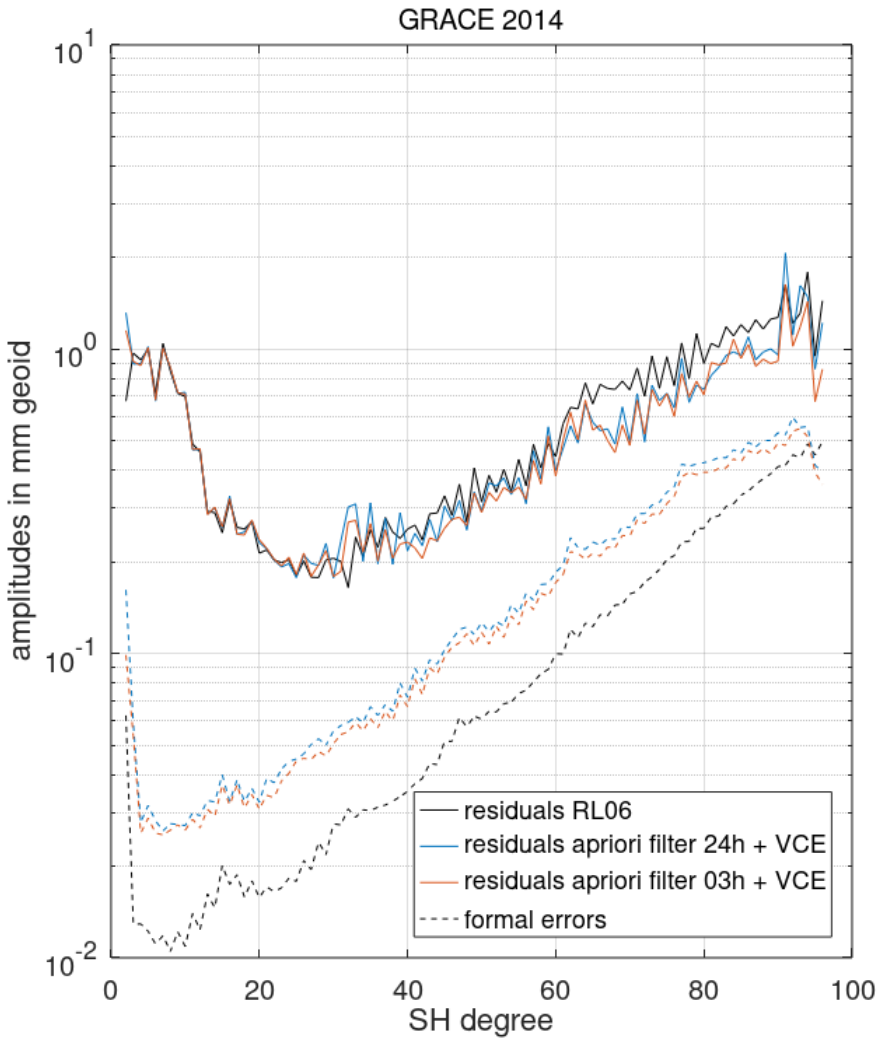
- Covariance functions from noise PSD models → Variance covariance matrix
- Inversion and Cholesky decomposition → Weighting/filter matrix



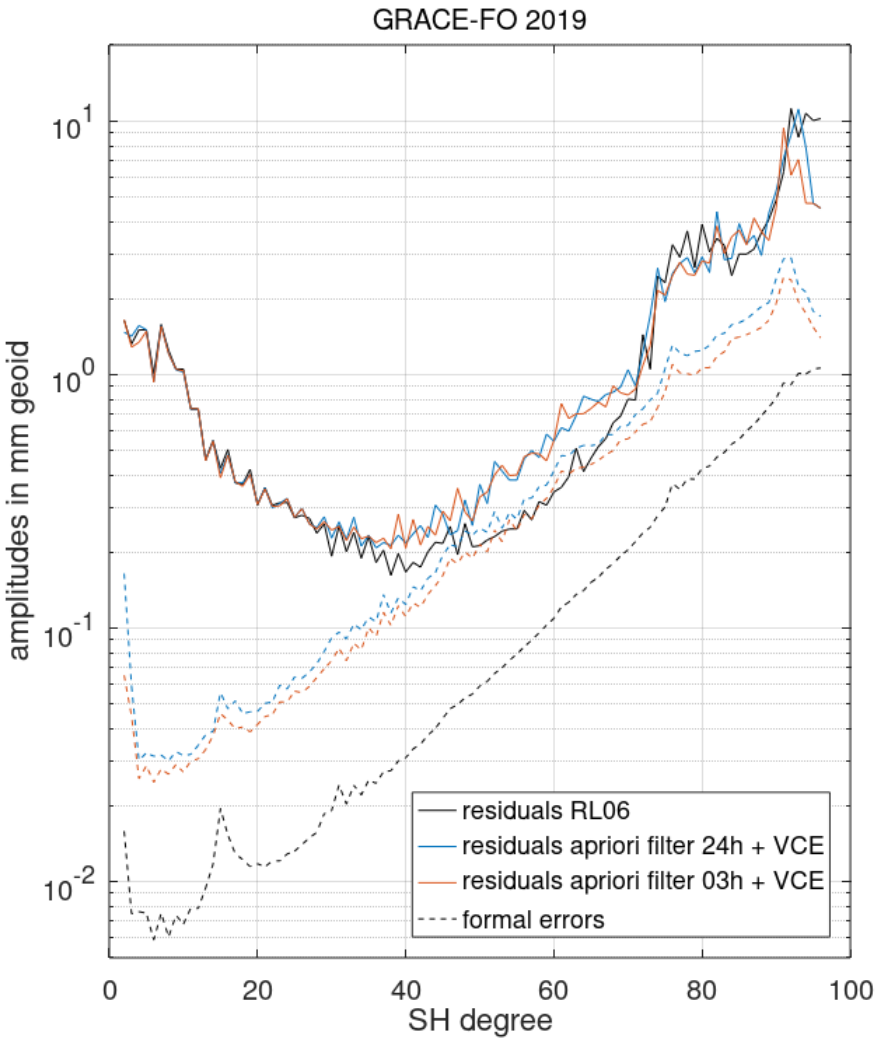


1. IP4: GRACE KRR filter test

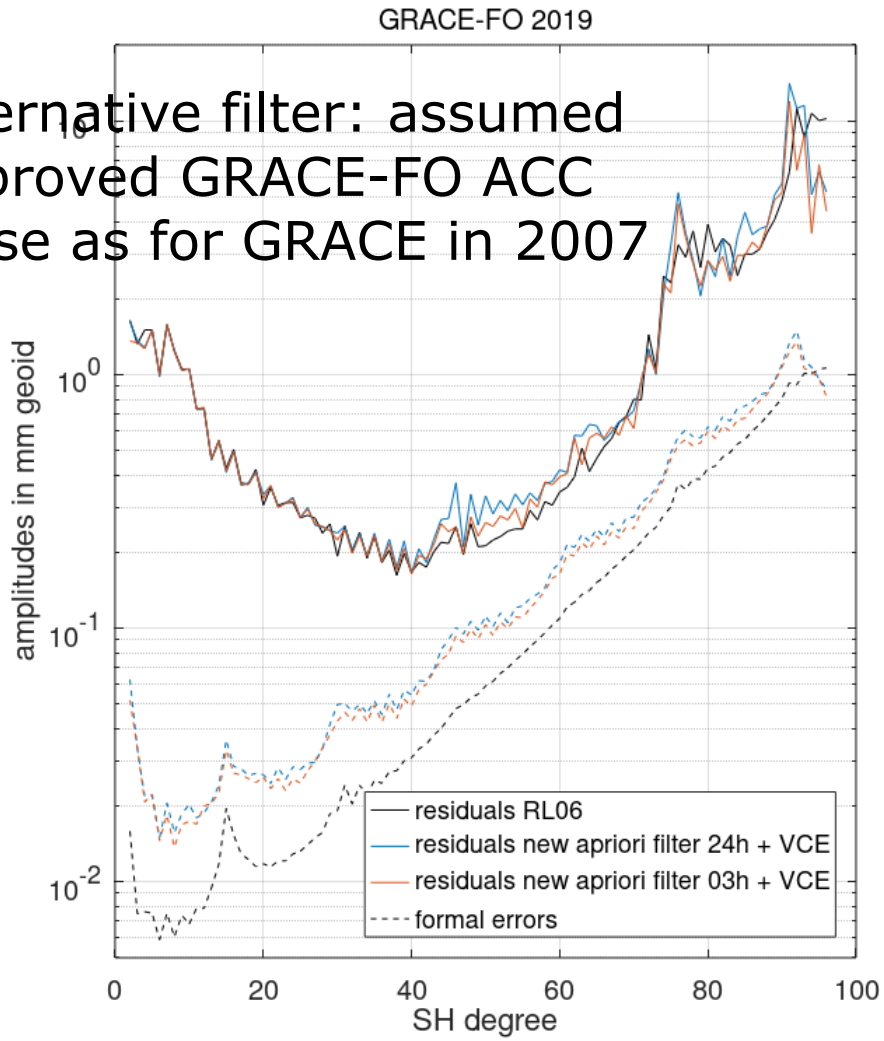




1. IP4: GRACE-FO KRR filter test for 2019/11



Alternative filter: assumed improved GRACE-FO ACC noise as for GRACE in 2007



First part conclusions

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Instrument performance

- GRACE ACC dominating the lower frequencies below 5 mHz of the ranging observations
- Constant GRACE/GRACE-FO ranging noise PSD model seems to be sufficient (GRACE KBR noise larger than GRACE-FO KBR noise by a factor of 2)

GRACE/GRACE-FO KRR weighting tests

- Improved (more realistic) formal errors in all cases
- Indication of slightly improved (smaller high SH degree amplitudes) solutions compared to RL06 for some cases
- 3 hours filter lengths seems to be better than 24 hours
- Initial GRACE-FO ACC noise assumption seems to be pessimistic
- Iterative filter procedure with postfit residual analyses required

2. IP5: Improved stochastic modelling

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IP5 final aim: Improved stochastic modeling for the background models (ocean tides and AOD1B product) in real-data processing

→ Simulation studies can help to identify the parameters of the background models which have to be modelled stochastically in GRACE/GRACE-FO real-data processing

Monte-Carlo method allows to simulate the stochastic behaviour of the models by varying the model parameters within given ranges taking into account the correlations between them

→ The variation ranges and correlations between model parameters should be known and given by their Variance-Covariance Matrix (VCM)

We performed Monte-Carlo simulations for the AOD1B product and ocean tidal model

2. IP5: Monte-Carlo approach for simulations

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Monte-Carlo approach to simulate stochastic variations in AOD1B product:

1. we take a normally distributed random vector **r**
   - its length equals the number of parameters in AOD1B which we want to vary
   - mathematical expectation for **r** is 0, variance is 1
2. we take the VCM for the AOD1B product: provided by NEROGRAV IP2, full matrix up to d/o 30
   - perform Cholesky decomposition of the VCM: VCM = $L*L^T$, where L is triangular matrix
3. we obtain (L***r**), a random vector with mathematical expectation = 0, its variances and correlations are given by the used VCM

Varied AOD1B values = original AOD1B + L***r**

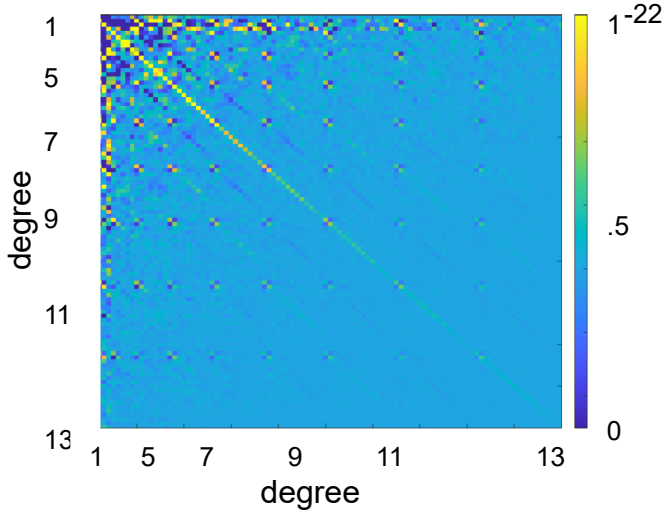
2. IP5: Monte-Carlo for simulations of AOD1B

Using the described Monte-Carlo approach, we computed 30 AOD1B variants for January 2007 and 30 GRACE real-data solutions for January 2007, which differ only by the used AOD1B model

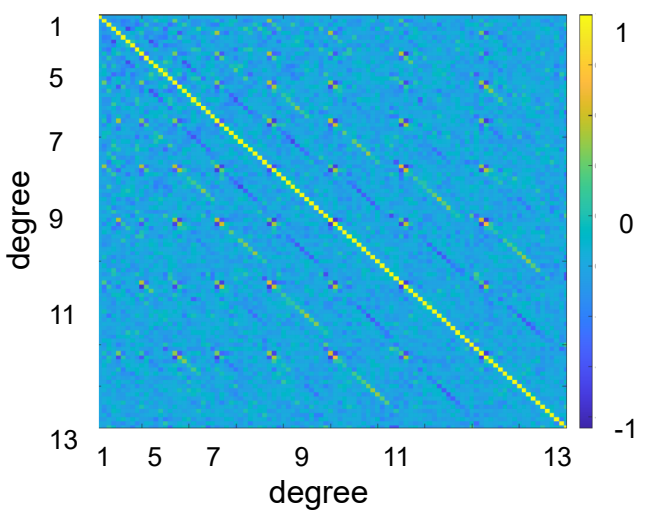
- 30 GRACE real-data solutions, gravity field estimated till d/o 60
- Standard Deviation (STD) for each gravity field coefficient

Used full-VCM (available till d/o 30, plotted for readability reasons till d/o 13) and respective correlations:

Variance/Covariance Matrix (till d/o ~13)



Correlation Matrix (till d/o ~13)

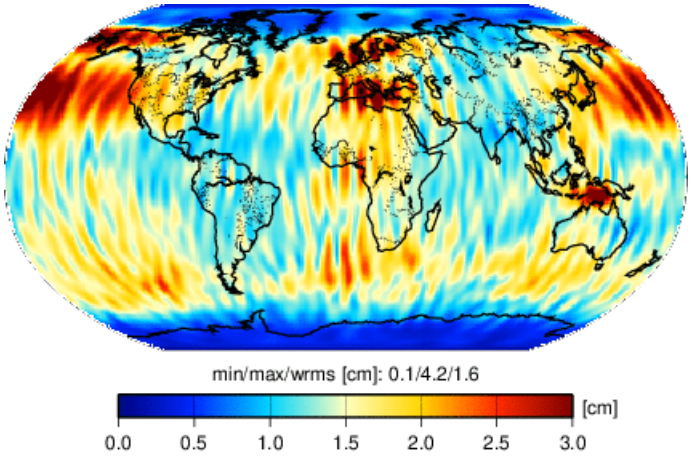


2. IP5: Monte-Carlo for simulations of AOD1B

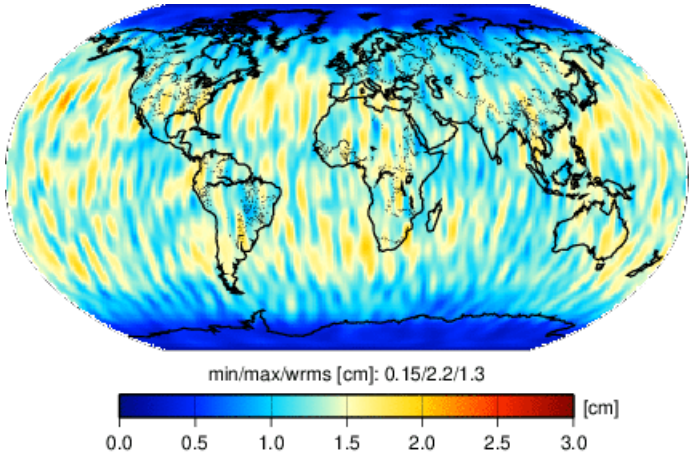
Test:
30 AOD1B-models varied with the full-VCM till d/o 30 vs.
30 AOD1B-models varied using only diagonal elements from VCM

We plot STDs (standard deviations) from 30 solutions for each gravity coefficient on a grid as EWH (equivalent water height [cm])

full VCM



diagonal elements from VCM

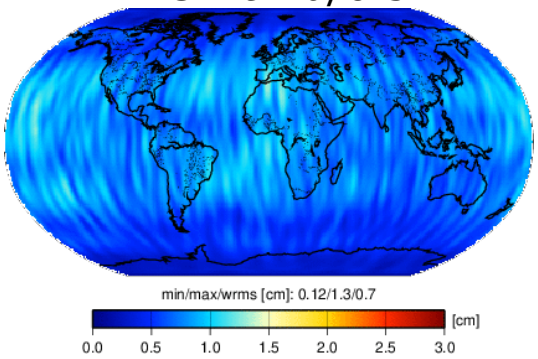


→ Geographical structure in estimated gravity field is caused by the correlations between AOD1B parameters

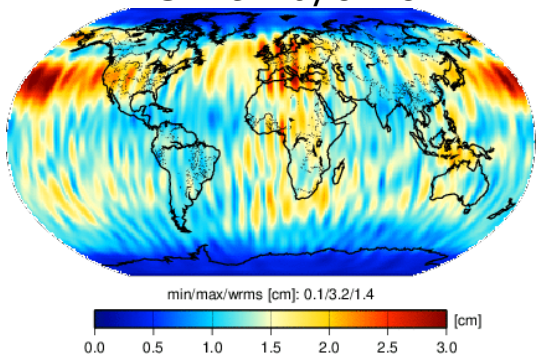
2. IP5: Monte-Carlo simulations of AOD1B

To test, till which d/o the AOD1B-variations influence the estimated gravity field, we varied the AOD1B product till d/o 5, 10, 15, 20, 25 and 30 using the full VCM (cutted till respective d/o), and considered the STDs of the estimated gravity field coefficients

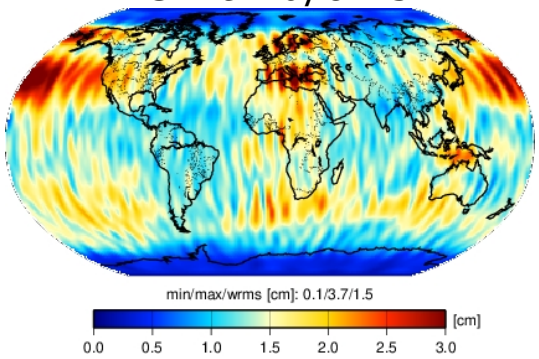
VCM till d/o 5



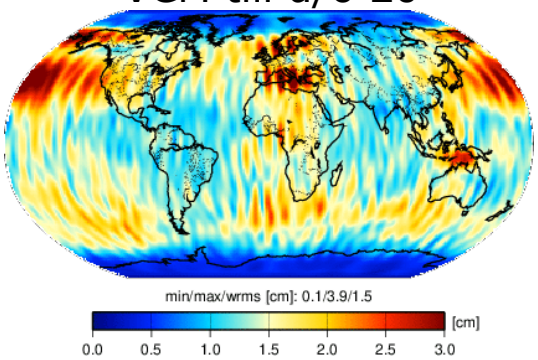
VCM till d/o 10



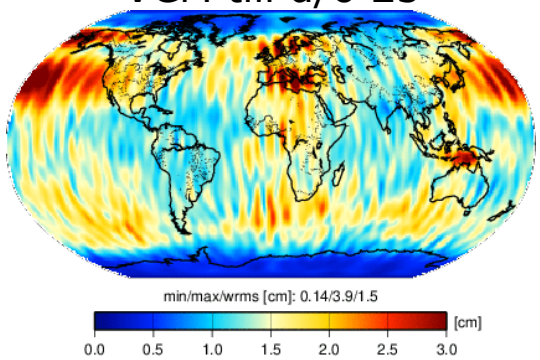
VCM till d/o 15



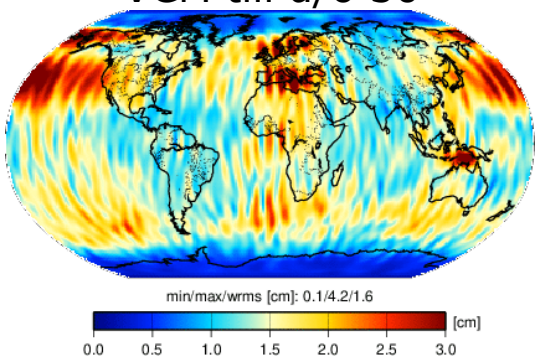
VCM till d/o 20



VCM till d/o 25



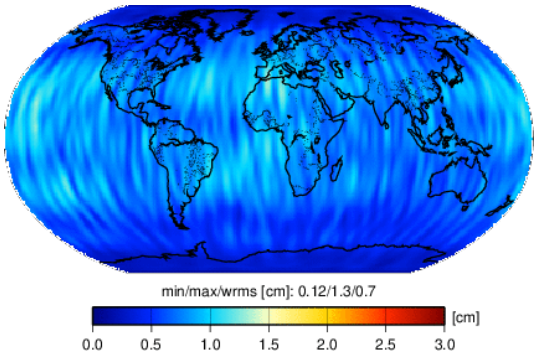
VCM till d/o 30

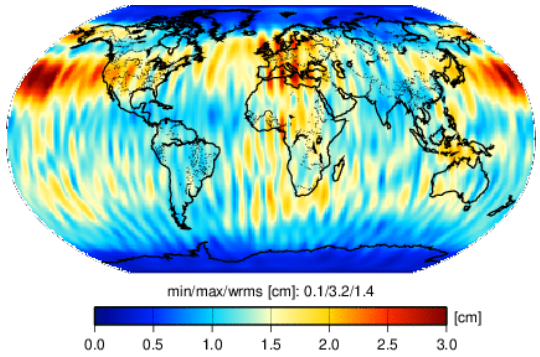


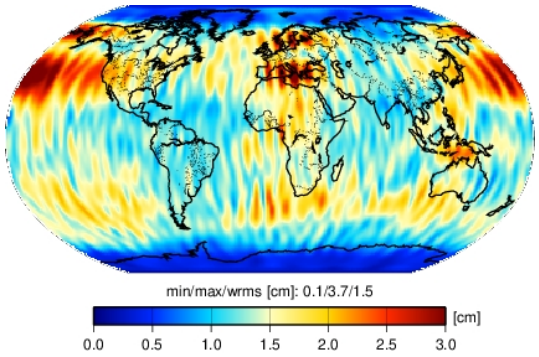
2. IP5: Monte-Carlo simulations of AOD1B

Amplitudes of AOD1B coefficients decay quickly for higher degrees

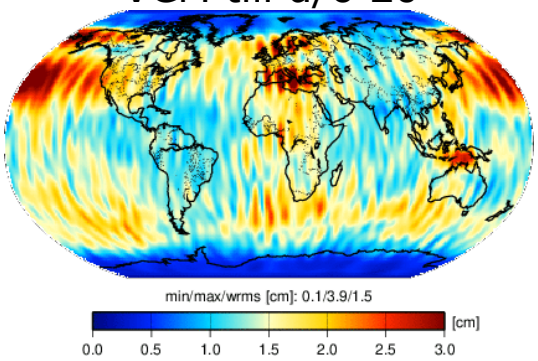
- → Variations in higher degrees have nearly no influence.
- → Nearly no visible changes in pictures after d/o 15.
- → Only very small changes in maximum, minimum and rms-values after d/o 15.



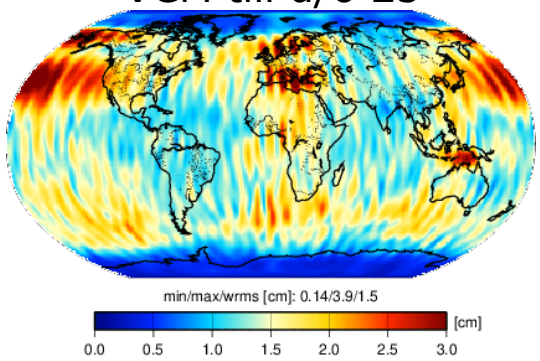




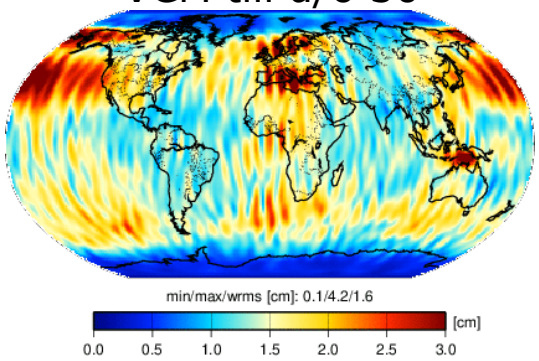
VCM till d/o 20



VCM till d/o 25



VCM till d/o 30

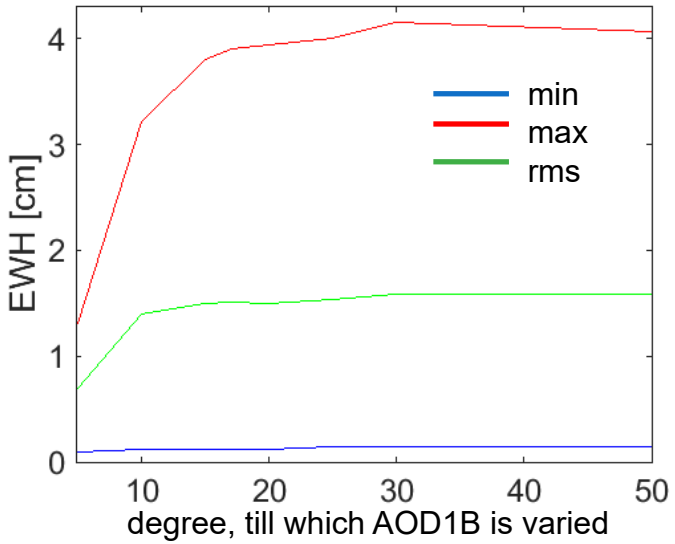


2. IP5: Monte-Carlo simulations of AOD1B

Additionally, we used a VCM consisted of the full VCM till d/o 30 and of only diagonal elements between d/o 31 and 180. Diagonal elements were computed as mean values from the AOerr product [Dobslaw et al. 2016, doi:10.1007/s00190-015-0884-3]

We show the minimum, maximum and rms-values for the equivalent water heights, obtained with AOD1B-variations till d/0 5, 10, 15, 20, 25, 30 and 180 (cut at 50 in the plot)

→ Nearly no changes after d/o 15



Conclusion: the AOD1B coefficients should be modeled stochastically in the real-data processing till at least d/o 15

2. IP5: Monte-Carlo simulations for tidal model

We used the same Monte-Carlo approach to simulate variations in the ocean tide model FES2014.

FES2014: spherical-harmonic expansion for 33 tidal waves up to d/o 180

Initial assumption for the tests: VCM consisting of only diagonal elements computed as 7% of the signal. This approach, while neglecting the correlations between different spherical-harmonic coefficients, allows to easily test the influence of the ocean tide model up to high degrees and for all tidal waves on the estimated gravity field.

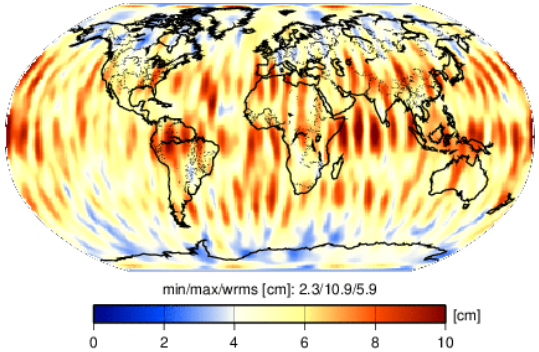
The NEROGRAV IP1 has provided the full VCMs up to d/o 30 for 8 main tidal waves, which will be used in the processing of real-data.

2. IP5: Monte-Carlo simulations for tidal model

Monte-Carlo variations of ocean tidal model FES2014:
VCM with only diagonal elements computed as 7% of the signal

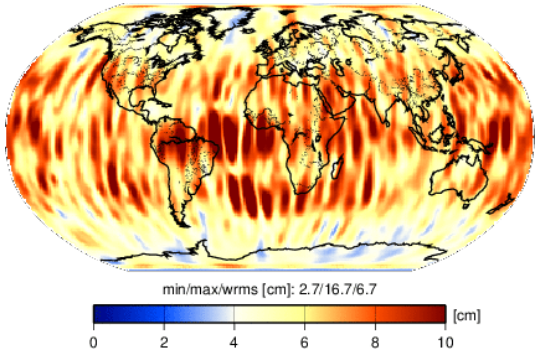
RMS of estimated gravity field coefficients (till d/o 60), plotted on grid as EWH [cm]

all 33 waves changed, till d/o 180

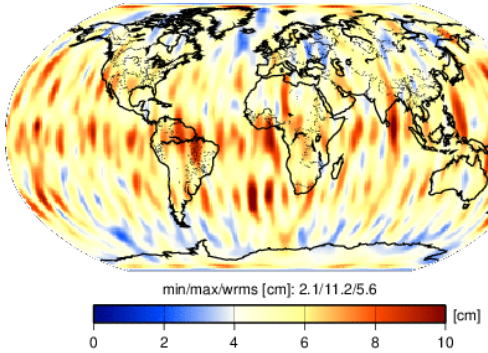


higher variability though less waves were varied

8 main waves changed, till d/o 180



8 main waves changed till d/o 30



2. IP5: Monte-Carlo simulations for tidal model

Remarks to Monte-Carlo variations of the FES2014 model:

- unlike spherical harmonics of AOD1B product, whose amplitudes decay significantly for higher degrees, the spherical harmonics for ocean tides have approximately the same amplitudes up to d/o 180
- as a result, the variations in high degrees of the ocean tide model influence the solution not less than the lower degrees
- as seen from the test where all 33 FES2014 tidal waves were varied, additional tidal waves can compensate the errors for the initial main waves.

Conclusion: since the impact of high degrees of ocean tides is not negligible, we need to use all available stochastic information of ocean tides.

→ full VCMs for 8 main tides till d/o 30 are available from NEROGRAV IP1 and will be used in real-data processing

Second part summary

- Monte-Carlo simulations of stochastic behaviour of AOD1B-product show that the spherical-harmonic coefficients till at least d/o 15 should be modelled stochastically in the processing of the real GRACE/GRACE-FO data.

- For ocean tide models all available stochastic information should be used in the future processing.

- For future real-data GRACE/GRACE-FO processing we will use full static VCMs till d/o 30: the VCM for AOD1B product is provided by the NEROGRAV IP2, the VCMs for 8 main tidal waves are provided by the NEROGRAV IP1.