

EGU21-12257 G4.2

Evaluation of Pendulum NGGM Scenarios by Full Closed-Loop Simulation

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11:45–15:00 (CEST)



CENTER OF
APPLIED SPACE TECHNOLOGY
AND MICROGRAVITY

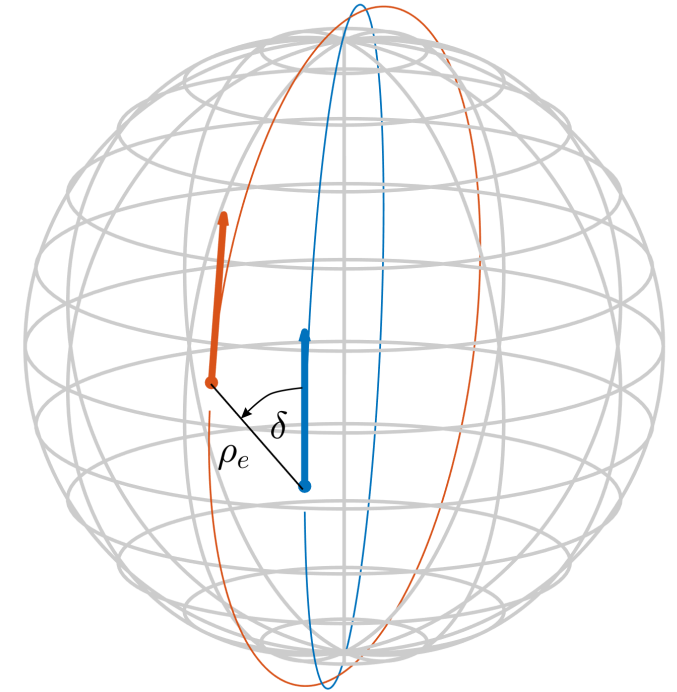


Outline

- ▶ Overview
- ▶ Forward Simulation
- ▶ Sensor Models
- ▶ Background Model Errors
- ▶ Gravity Field Recovery (GFR)
- ▶ Presentation of Results
- ▶ Results in Spectral Domain
- ▶ Results in Spatial Domain
- ▶ Conclusions

Overview

- ▶ Investigation of Pendulum NGGM Scenarios via full numeric simulation
- ▶ Pendulum configurations are investigated for:
 - Different opening angles δ (0° , 15° , 30° , 45° , 60° , 75° , 85°)
 - Different errors in background models (Ocean tide and two AOD error models)
 - Different sensor models, mainly KBR and LRI
 - Different satellite separations (mean distance: $\bar{\rho} = 120, 200, 280$ km)
- ▶ As reference a GRACE-like ($\delta = 0^\circ$) and a Bender (two pairs, one polar and one with 63° inclination) scenario are considered for comparison
- ▶ Gravity Field Recovery (GFR) based on classical variational-equation approach
- ▶ Modeled and used observations for GFR: Orbit solution, range-rate, accelerometer and attitude data
- ▶ No special or adapted processing for the different scenarios is applied



Pendulum angle δ defined as angle between velocity and line of sight direction at equator (proportions enlarged to better demonstrate conditions)

Forward Simulation

Definition of Scenarios and Generation of Orbit

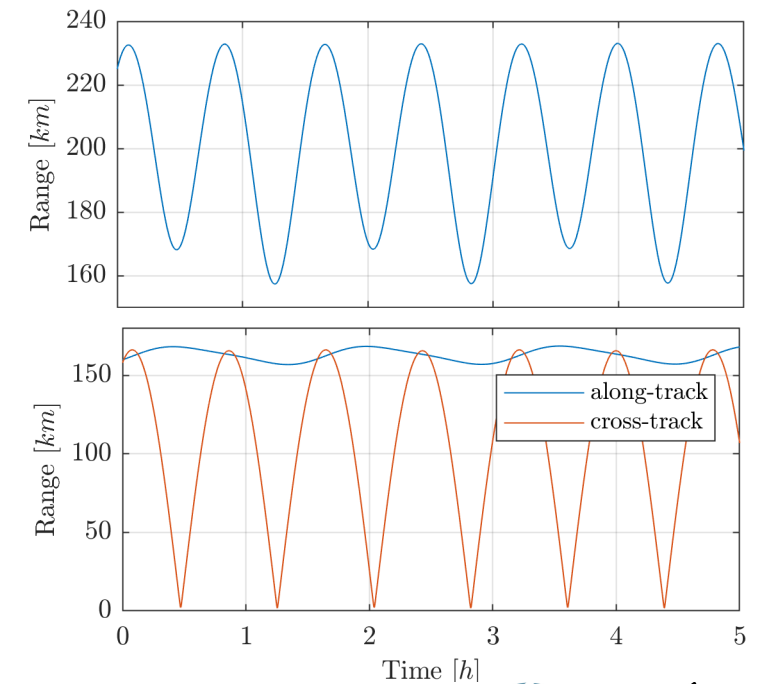
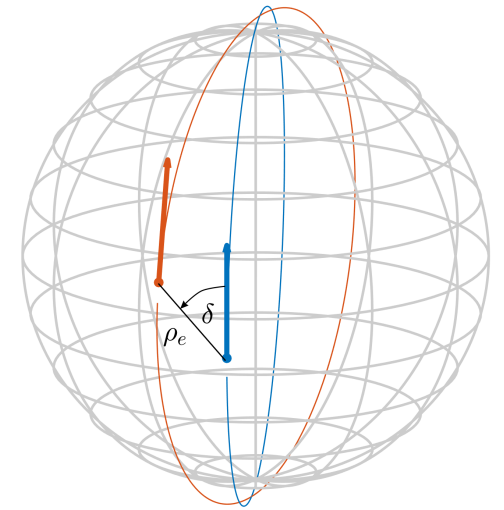
Scenario Definition

- ▶ For the first satellite always the same initial conditions are used from GRACE A, 2005-05-01
- ▶ The position of the second satellite is varied to obtain a desired mean satellite distance and pendulum angle δ
- ▶ The actual distance may distinctly vary, especially for higher pendulum angles δ , see plot

Orbit Integration

- ▶ For each Scenario data for 12 days are generated
- ▶ GOCO06s model for static gravitational field and time dep. HIS signal
- ▶ EOT11a in forward simulation, FES14b in GFR
- ▶ Different AOD error models applied in GFR as background model
- ▶ Precise non-gravitational force modeling based on GRACE satellites
- ▶ In forward simulation and GFR 5 s sampling is used with the same numerical integrator (ABM 8) → hence no integration errors in results

Pendulum angle δ defined as angle between velocity and line of sight direction at equator



Top: Inter satellite distance for pendulum configuration with $\delta = 45^\circ$ and mean distance of 200 km, **bottom:** Separated in along-track and cross-track direction

Forward Simulation

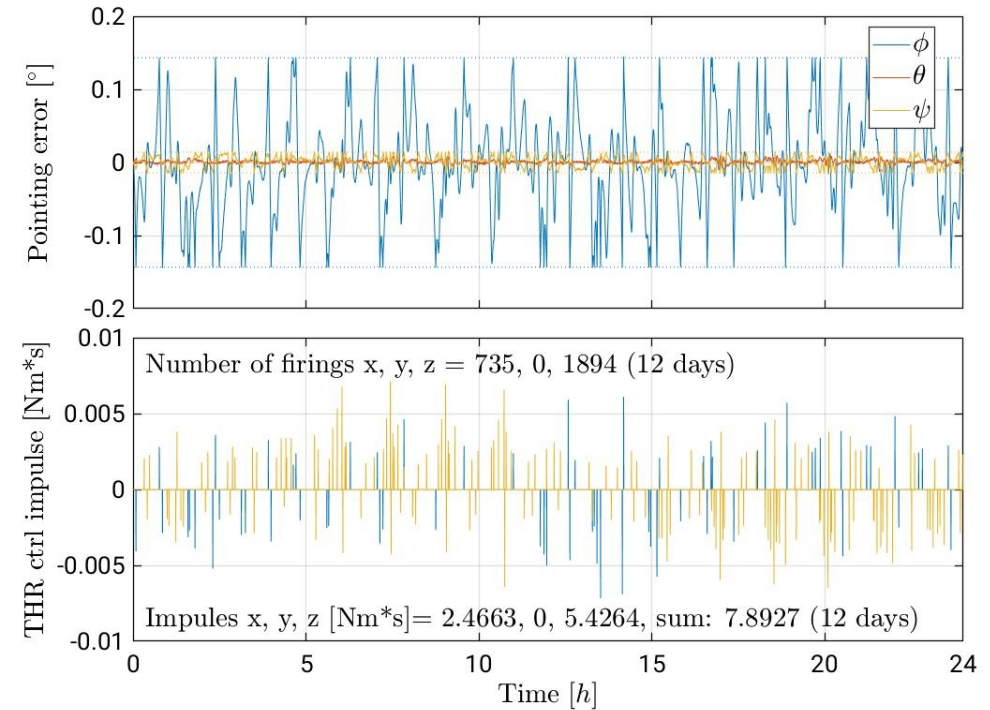
Attitude Control System (ACS)

- ▶ Complete simulation of ACS with magnetic torquer and thruster firing actuator models (GRACE-FO reference pointing tolerances)
- ▶ Controller logic adapted from GRACE/GRACE-FO, as we described in (Mashtakov et. al., 2020)
- ▶ Until pendulum angles up to $\delta = 30^\circ$ the same ACS scheme is working well but with increased energy expense:

For mean satellite distance 200 km, 12 days	Thruster firing momentum [Nm*s]	Mag. torquer momentum [Nm*s]
GRACE-like	7.9	38.9
GRACE 63° inclined	16.1	48.4
Pendulum $\delta = 15^\circ$	26.8	103.8
Pendulum $\delta = 30^\circ$	71.5	253.0

Required firing and magnetic torquer angular momentum for the different configurations, over the course of 12 days. Same ACS scheme and satellite geometry

- ▶ For pendulum angles bigger 30° , the ACS and/ or satellite geometry needs to be optimized, here we assume a perfect pointing with the attitude sensing error defined on page 9

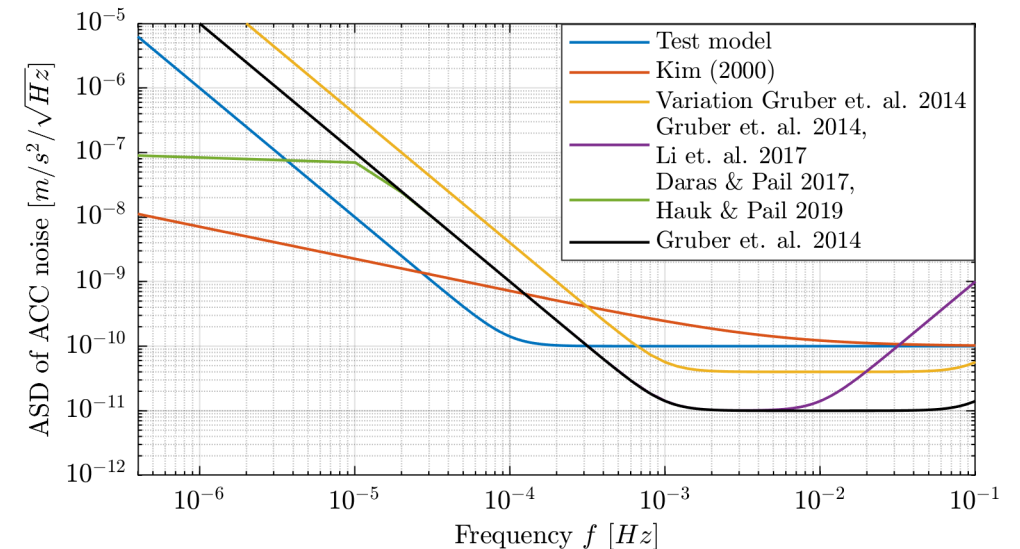


- ▶ GRACE-like ($\delta = 0^\circ$) attitude control results from simulation, **top:** Error from reference pointing (line of sight) expressed in Euler angles, and **bottom:** Thruster firing impulses for each axis

Sensor Models

Accelerometer (ACC)

- ▶ Several instrument models exist, usually given in terms of ASD noise models. Some prominent ACC examples shown →
- ▶ The mid frequency noise for most shown models is the limiting factor for GFR, thus the small high-frequency noise level ($1e-10 \dots 1e-11 \text{ m/s}^2$) is not that relevant, as well as the increasing slope of the **violet** model (Li et. al.) for high frequencies
- ▶ The **yellow** model has a really high low-frequency noise (not reasonable), heavily affecting the GFR results
- ▶ The low-frequency noise of **green** and **red** (Daras & Pail, Kim) models are too small compared to GRACE accelerometers (maybe reasonable for calibrated ACC)
- ▶ We use the black model (Gruber et. al.) for all cases in this study, applied to all three accelerometer axes (for each axis and satellite a different realization is generated)



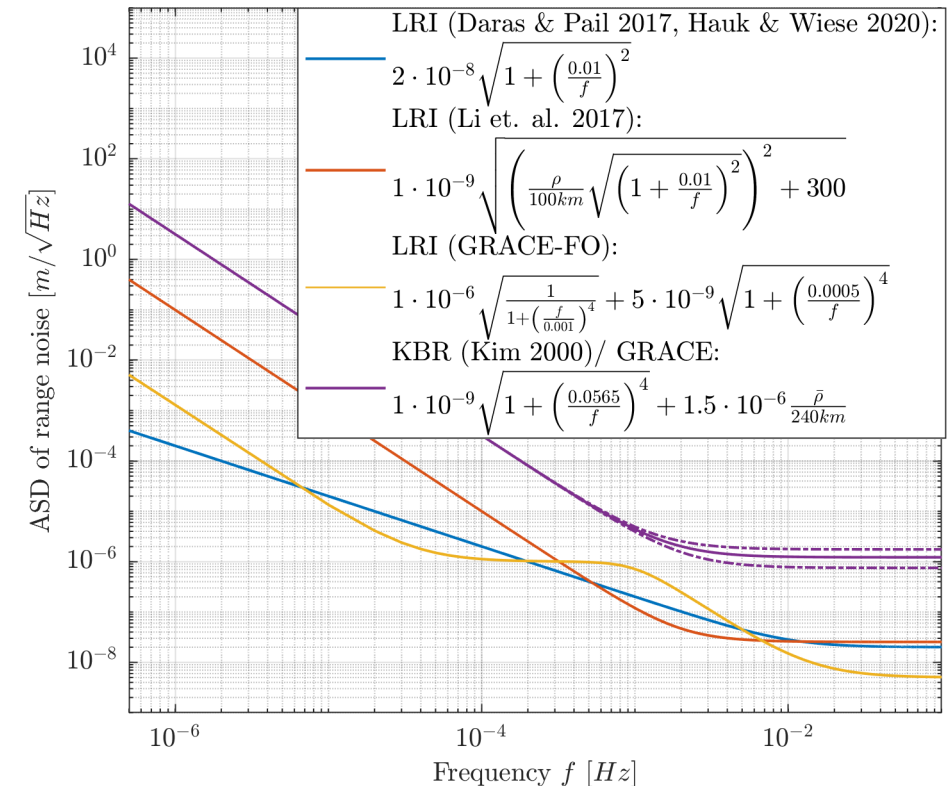
Some prominent and recently used accelerometer (ACC) noise models, here the black one is used

Sensor Models

Inter Satellite Ranging: KBR

KBR:

- ▶ The used model is based on GRACE and (Kim, 2000)
- ▶ The high-frequency noise is range dependent. It is used as stationary noise with the mean satellite distance (KBR mean) and as time dependent model with the actual distance (KBR var)
- ▶ Just the white noise part of the high frequencies is range dependent (120 – 280 km **violet dotted**)
- ▶ → The differences between the mean and variable model are very small, even for the highly changing distance of some of the investigated pendulum configurations, see in results (eg. page 14)
- ▶ The range-rate noise is obtained by numerical derivation of the range noise.



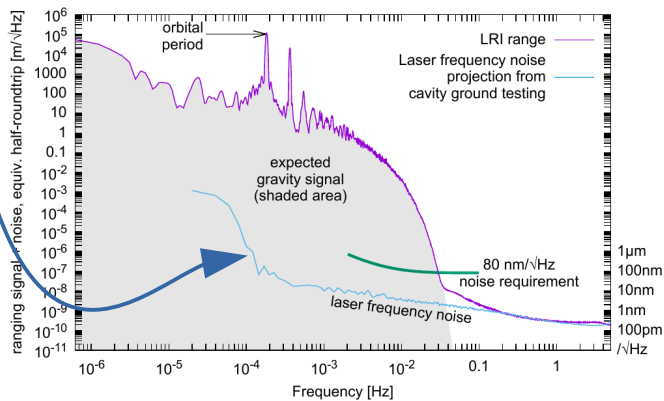
Some prominent ranging noise models for KBR and LRI, with its defining equations and the used **KBR** model

Sensor Models

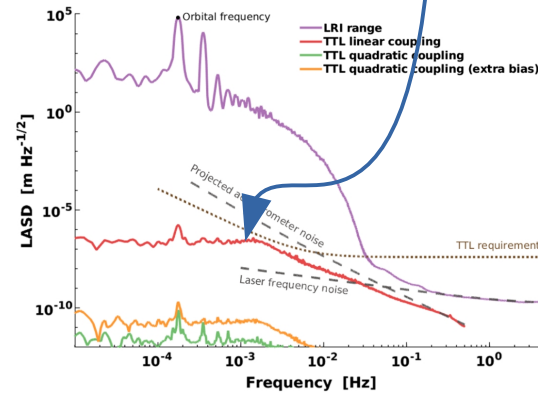
Inter Satellite Ranging: LRI

LRI:

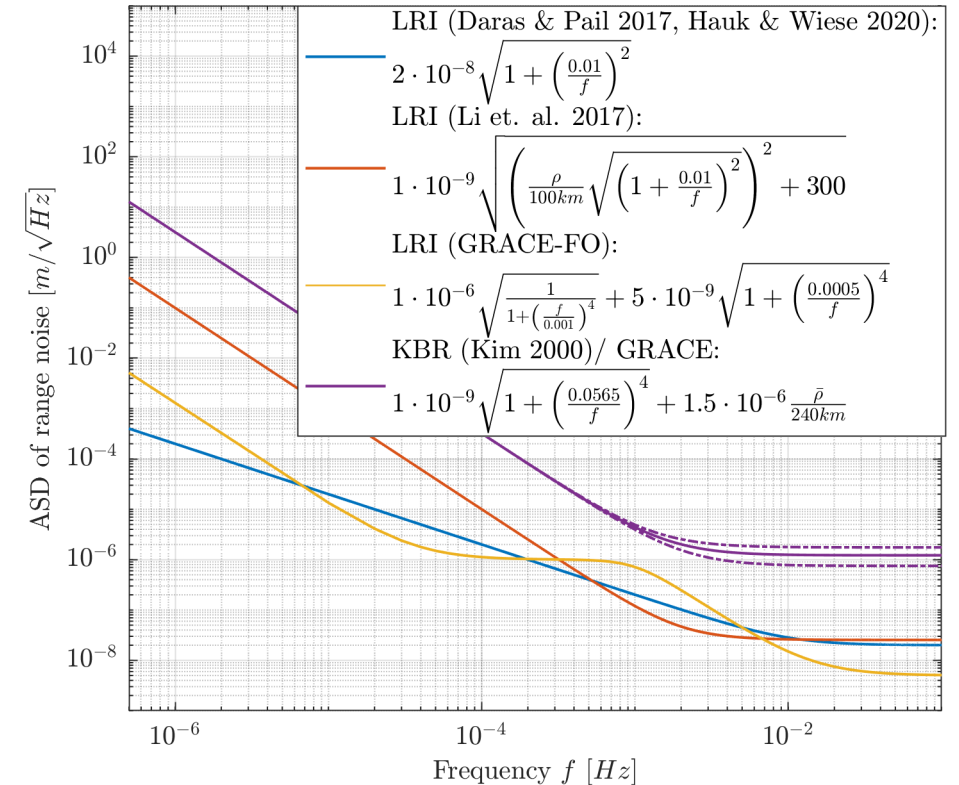
- ▶ The **yellow** LRI model is applied here, based on GRACE-FO
- ▶ The high and very low frequencies are limited by laser frequency noise (TR. Conklin et. al. 2020)
- ▶ In the mid frequencies it is limited by tilt-to-length-coupling (Wegener et. al. 2020)



Conklin et. al., 2020



Wegener et. al., 2020



Some prominent ranging noise models for KBR and LRI, with its defining equations and the used **LRI** model



Sensor Models

Orbit and Attitude Solution

Orbit solution (GNV or KOS):

- ▶ Position data used as GFR observations are generated by adding white Gaussian noise with $\sigma = 2$ cm

Attitude Solution (SCA):

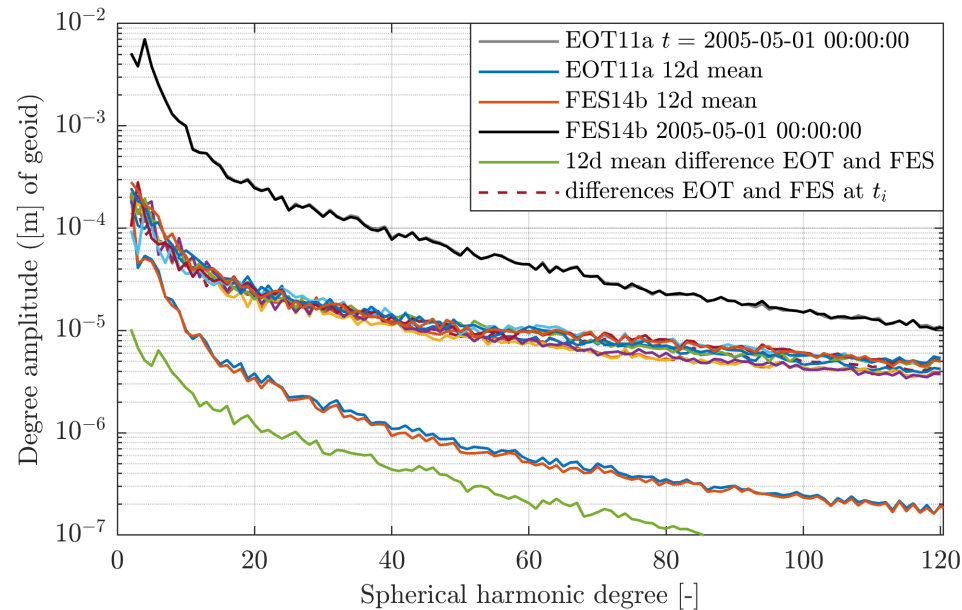
- ▶ Attitude sensing error based on the GRACE-like combination of two star cameras, with white Gaussian noises of 40 and 5 arc sec for boresight and perpendicular directions, respectively
- ▶ Compared to the accelerometer noise it is more or less negligible
- ▶ Time series for all noise models are generated with the LTPDA toolbox (<https://www.elisascience.org/ltpda/>) with 5 s sampling and for 30 days, thus the lowest frequencies in the noise models are about $1/30\text{d} = 3.86\text{e-}7$ Hz

Background Model Errors

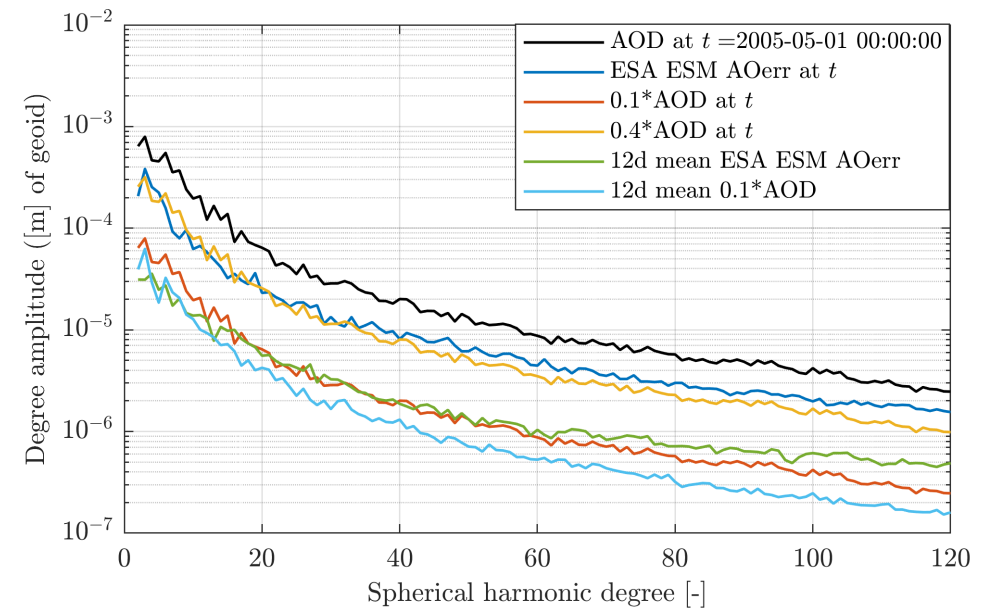
Ocean Tides (OT) and AOD

- ▶ Two different background model errors are assumed: Ocean tide and AOD errors (→ Discussion on next slide).
- ▶ OT error: Difference of EOT11a and FES14b models
- ▶ AOD error, two different models: 1. 10% of AOD1B model

2. AOerr from ESA Earth System Model (ESM) (Dobslaw et. al., 2015)



Ocean Tides



AOD

Background Model Errors

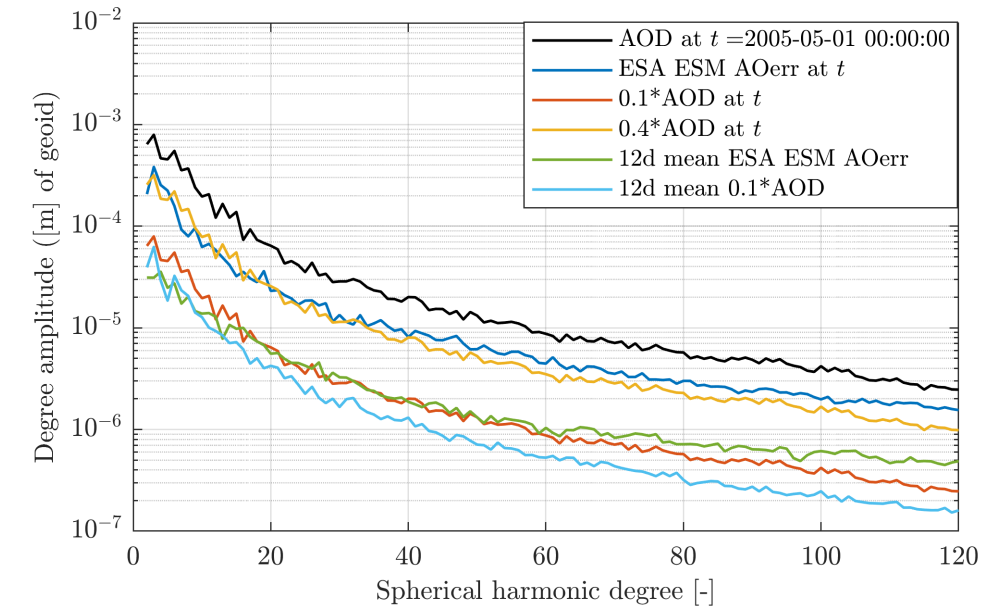
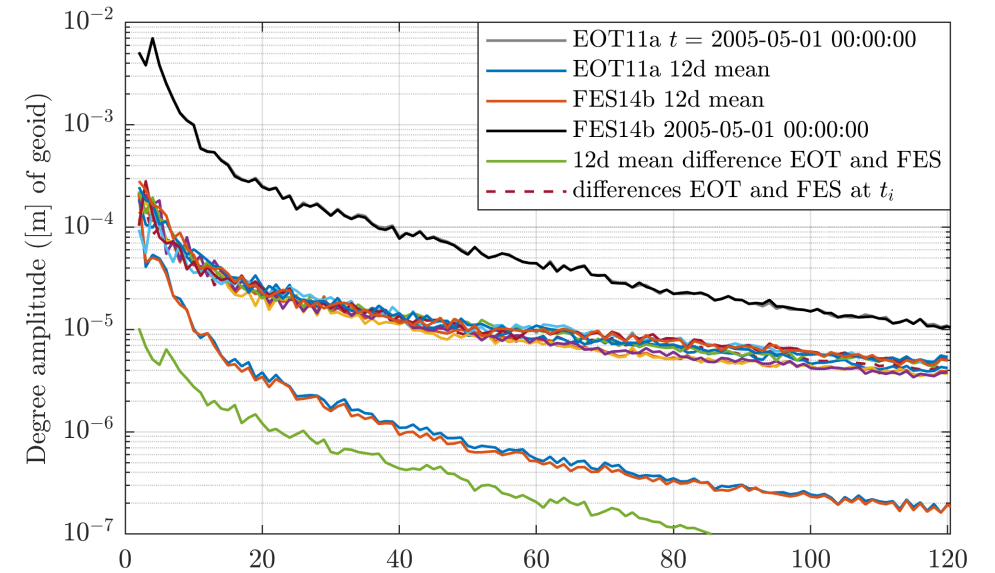
Discussion: Ocean Tides (OT) and AOD

Ocean Tides:

- ▶ The difference between EOT11a and FES14b models (= modeled OT error) is shown for several evaluations at some time points. It is relatively big
- ▶ In contrast to that, the mean of the models over 12 days is quite small (blue, red) and their difference (OT error) even smaller.

AOD:

- ▶ The total AOD signal (black) is smaller than the OT signal, but its mean is much bigger, also the mean of the errors is bigger (green, light blue, for the two different error models)
- ▶ The first AOD error model, 10% of the AOD signal (red) is rather small compared to the OT errors
- ▶ The second AOD error model from the ESM AOerr model (blue) is about 40% of the AOD signal (yellow), and its amplitudes are comparable to the OT error



Gravity Field Recovery

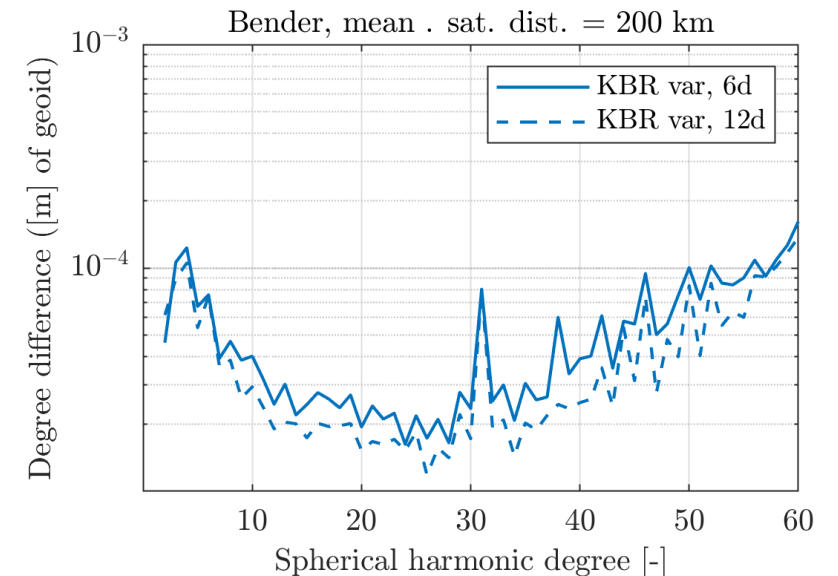
Scheme and Options

- ▶ Gravity Field Recovery (GFR) based on classical variational-equation approach
- ▶ Weighting of range-rate and 3d-position data via Variance Component Estimation (VCE)
- ▶ Parametrization: ACC calibration: bias + linear drift, 2h arc length
→ Optimized for ACC noise model
- ▶ No Variance-Covariance information of observations considered for weighting
- ▶ No special or adapted processing for the different scenarios is applied

- ▶ As “true” reference for the comparison of the results, the mean of the used time dependent GOCO06s model over the 12 days is used (the averaging errors are very small compared to the errors due to sensor noise and background model errors)

Presentation of Results

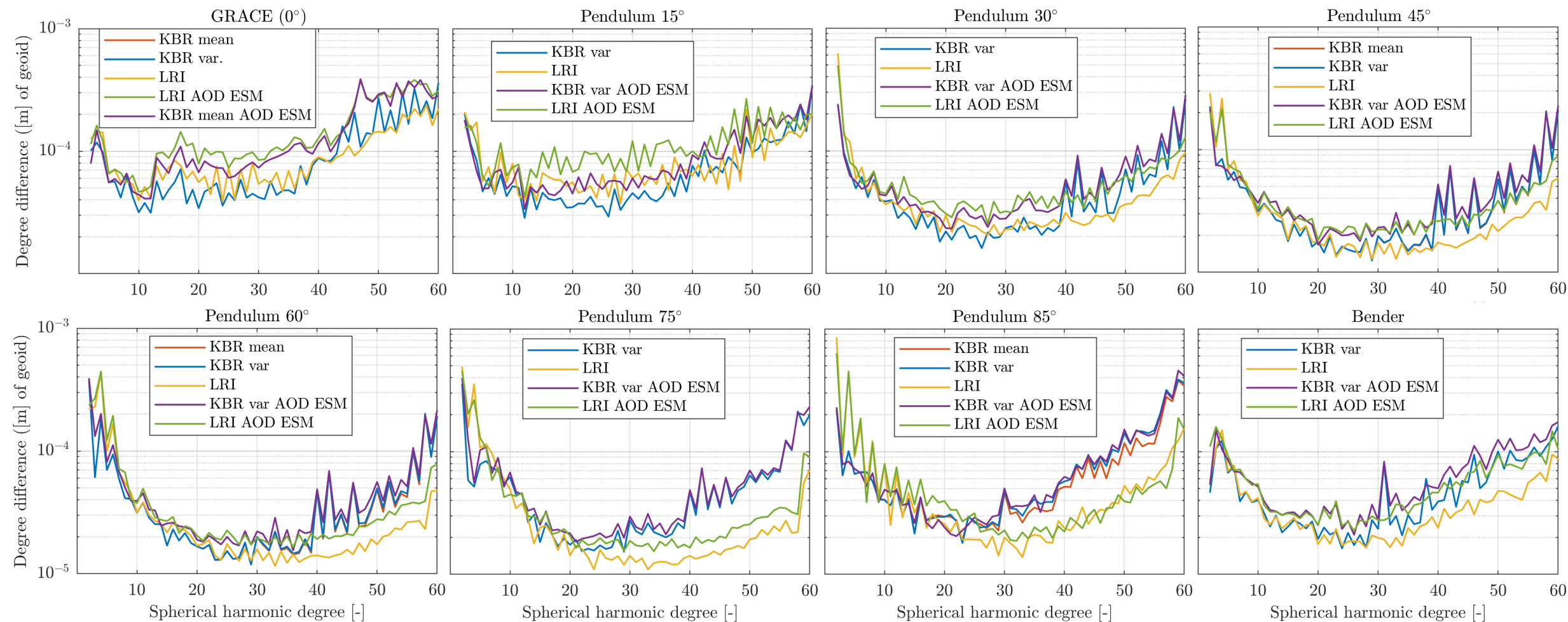
- ▶ For each configuration (Pendulum angle $\delta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 85^\circ$ and mean satellite distance $\bar{\rho} = 120, 200, 280$ km) four cases with different ranging noise and background error models are considered:
 1. KBR var ranging noise model, AOD error model 1 (10% AOD)
 2. LRI ranging noise model, AOD error model 1 (10% AOD)
 3. As case 1. (KBR var.), AOD error model 2 (AOD ESM)
 4. As case 2. (LRI), AOD error model 2 (AOD ESM)
- ▶ The Bender configuration is evaluated for the four cases and the three mean satellite distances, as well
- ▶ For a comparable amount of data, the Bender scenario with four satellites is just processed for 6 days (instead of 12). The effect of this data reduction is shown in the plot →
- ▶ The results are compared to the “true”, initially used gravitational model GOCO06s. Because it is time dependent, the mean over 6 or 12 days is used as reference



GFR results of Bender scenario with data of 6 and 12 days.

Results in Spectral Domain

Mean Satellite Distance 200 km

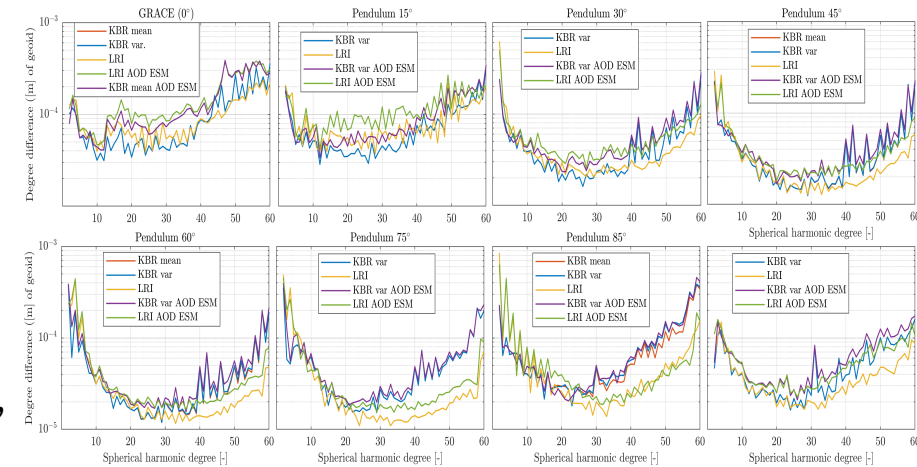


ZARM

Results in Spectral Domain, Discussion

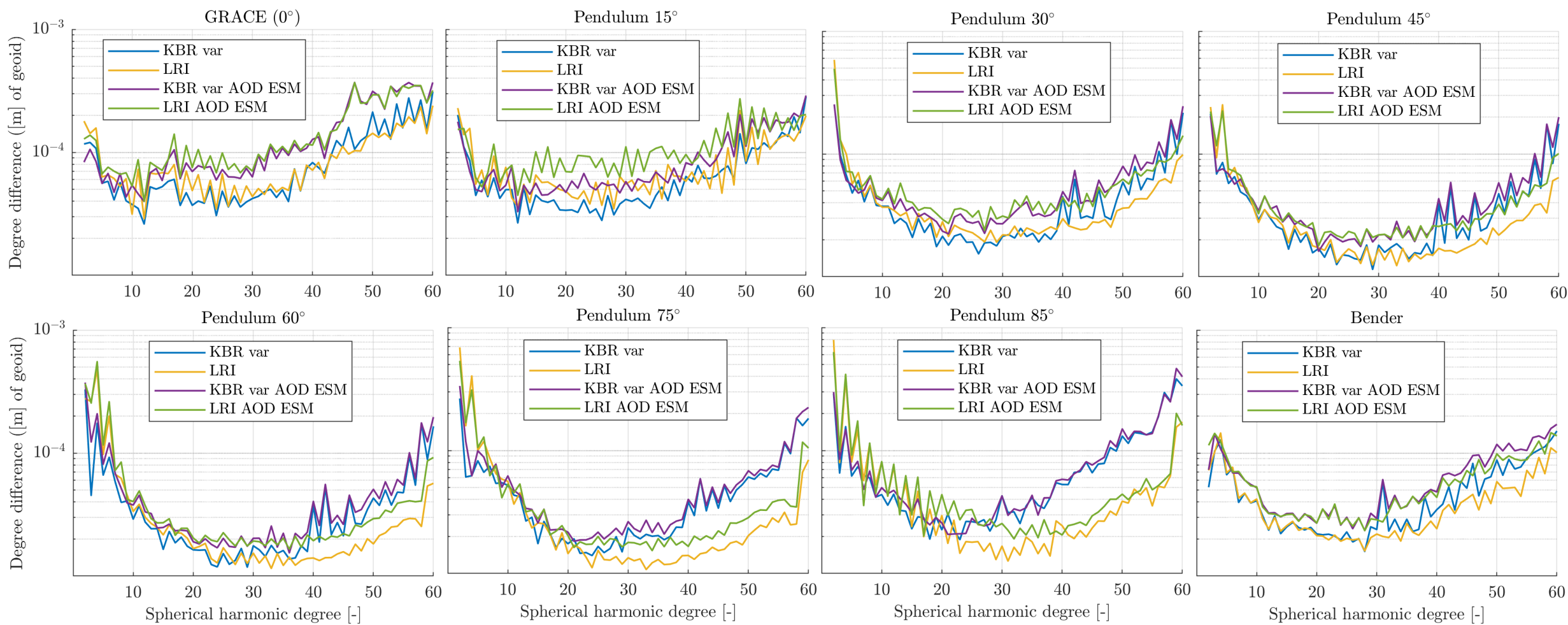
Mean Satellite Distance 200 km

- ▶ Errors of mid and high degrees are distinctly decreasing with bigger pendulum angles for all cases up to about $\delta = 75^\circ$
- ▶ Very low degrees are not as well recovered with bigger pendulum angles, the GRACE-like case ($\delta = 0^\circ$) and Bender configuration give better results
- ▶ LRI does not improve results for small pendulum angles (GRACE-like 0° and 15°) compared to KBR, as we also see in actual GRACE-FO analysis
- ▶ LRI distinctly improves the higher degrees for bigger pendulum angles ($30^\circ \dots 85^\circ$), but is slightly worse for the very low degrees compared to KBR
- ▶ Higher errors in the background models are better compensated by the pendulum scenarios with bigger angles compared to the GRACE-like and 15° case, for LRI and KBR. Also the Bender configuration is slightly worse than the bigger pendulum angles in that respect.
- ▶ Overall the degree differences for the bigger pendulum angles ($30^\circ \dots 75^\circ$) are better than for the Bender case, but for the very low degrees.
- ▶ The KRB var model compared to the KRB mean model (evaluated for $\delta = 0^\circ, 60^\circ, 85^\circ$) has barely an effect on the results, just slight differences are visible for $\delta = 85^\circ$



Results in Spectral Domain

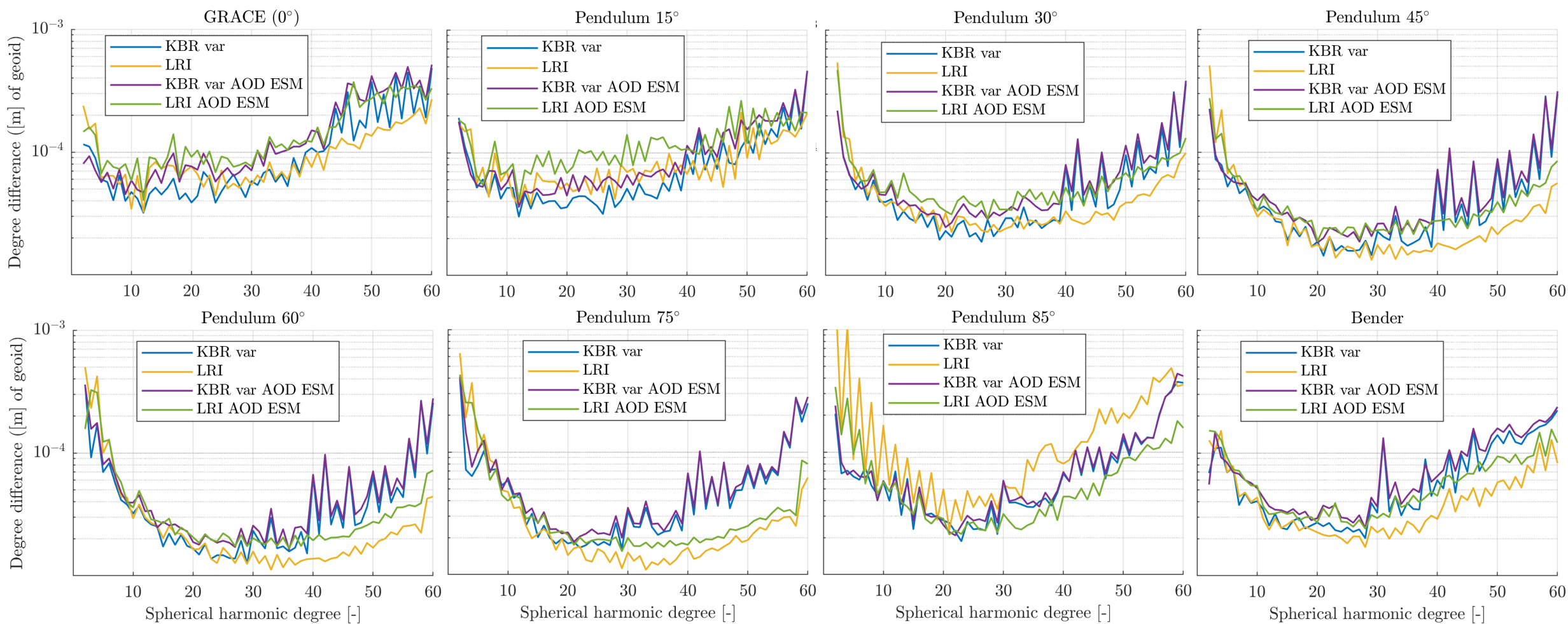
Mean Satellite Distance 280 km



ZARM

Results in Spectral Domain

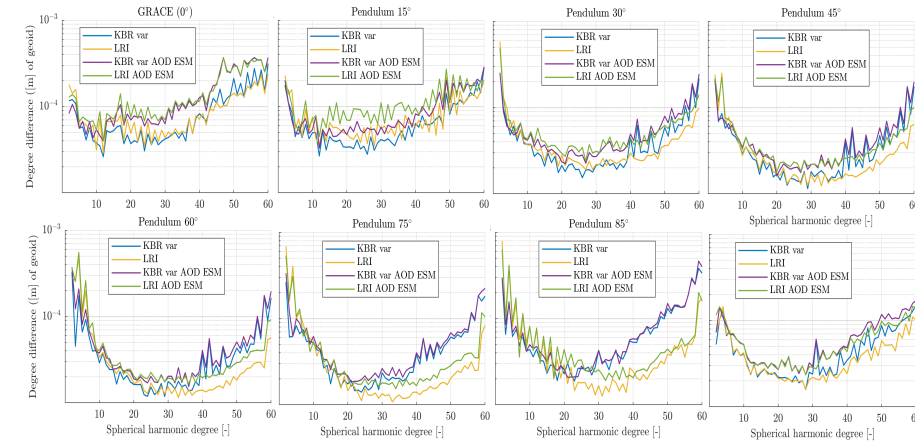
Mean Satellite Distance **120 km**



Results in Spectral Domain, Discussion

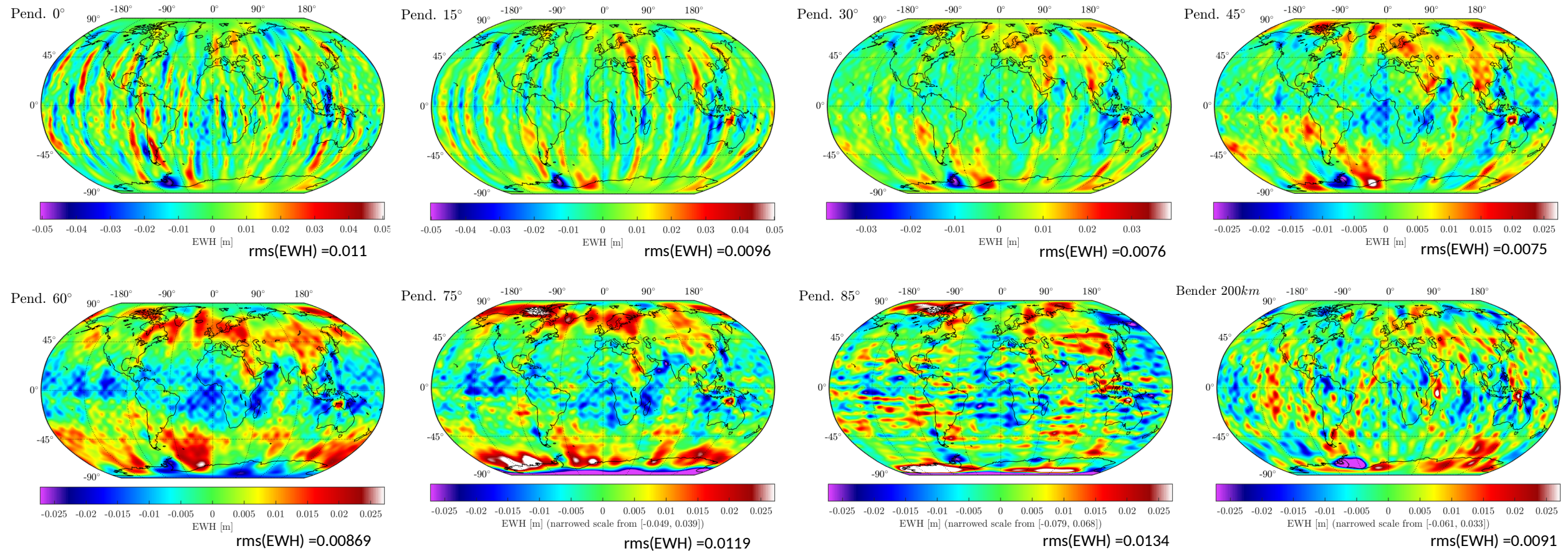
Mean Satellite Distance 280 and 120 km

- ▶ The shorter mean satellite distance of 120 km generally decreases the quality of the results for all cases
- ▶ Especially for the KBR instrument, the bigger mean satellite distances increase the solutions quality, particularly for the very low and high degrees, even though the KBR noise is higher
 - This finding is valid for GRACE-like, pendulum and Bender scenarios
- ▶ Comparing the 280 and 200 km cases, the larger distance slightly reduces some oscillation of the higher degree amplitudes, especially for KRB and for all scenarios
- ▶ In general the trends and findings from before do not change with the slightly shorter and longer mean satellite distance



Results in Spatial Domain in Terms of EWH

KBR var, Mean Sat. Dist. 200 km (scale not equal in all plots)

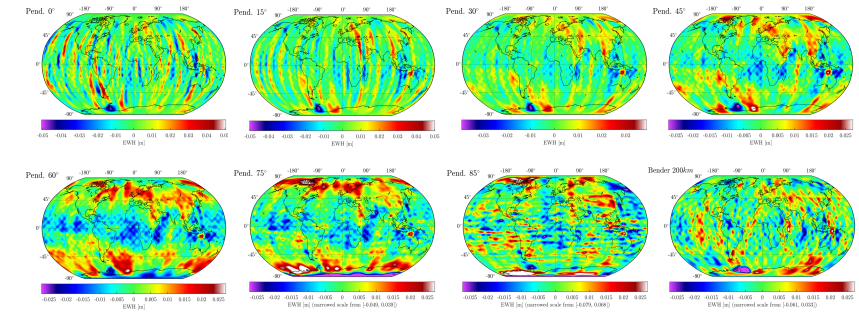


- ▶ All results are Gaussian filtered with 400 km radius
- ▶ The Pendulum solutions are spatially limited by the relatively high error of the low degree coefficients
- ▶ Qualitative comparison of spatial error distribution of all results by the spatial rms of the EWH

Results in Spatial Domain in Terms of EWH, Discussion

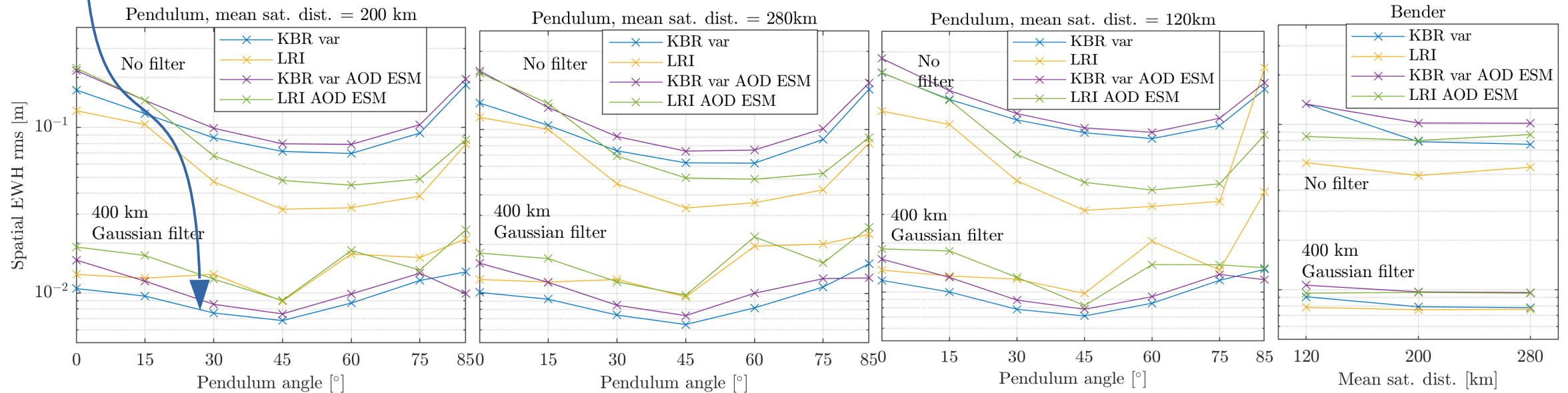
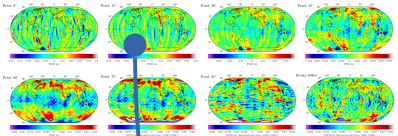
KBR var, Mean Sat. Dist. 200 km

- ▶ The pendulum configurations show a lower error level than the GRACE-like scenario, as well in spatial domain
- ▶ The prominent striping of the GRACE-like scenarios vanishes with higher pendulum angles
- ▶ The higher errors in the low degree coefficients result in a distinct north south error pattern for the pendulums with higher angles $\delta = 30^\circ, \dots, 85^\circ$
- ▶ This is spatially limiting the performance of the pendulum configurations
- ▶ Also the Bender scenario shows a much more isotropic and lower error pattern compared to the GRACE-like case
- ▶ From the global rms, the 45° pendulum scenario performs best, followed by the 30° and 60° pendulums and then the Bender configuration
- ▶ In the Antarctica region a prominent error is visible, more or less in each case, which is due to the ocean tide errors. It is least prominent for the two pendulum scenarios with 45° and 60°
- ▶ For the 85° pendulum, the typical north-south striping of the GRACE case shifts towards an east-west striping. This is reasonable because the main measurement direction is in that direction.



Results in Spatial Domain in Terms of EWH

For comparison condensed as spatial, scalar rms(EWH)



Spatial rms of the EWH for filtered (400 km Gaussian) and unfiltered solutions, for all cases

Results in Spatial Domain, Discussion

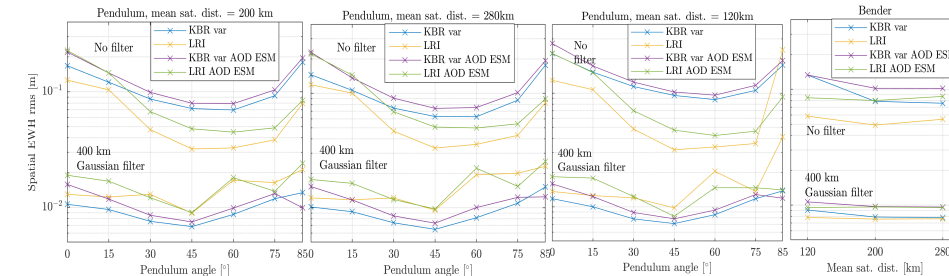
For comparison condensed as spatial, scalar rms(EWH)

Filtered solutions

- ▶ Results are very similar for the three mean satellite distances 120, 200 and 280 km
- ▶ The pendulums with δ between 30° and 60° give the lowest rms errors
- ▶ For the pendulum solutions with LRI, which showed very low errors for the higher degrees, the higher error in the very low degrees is dominating the representation and thus limiting the results in spatial domain.
- ▶ The higher background model errors are best compensated for δ between 30° and 60° for KBR and especially for LRI
- ▶ For the Bender configuration the differences between KBR and LRI are very small. No instrument (KBR and LRI) is advantageous for compensating bigger background model errors
- ▶ The LRI gives slightly better results for the Bender configuration. The LRI does not worsen the low degrees that much like for the pendulum cases.

Unfiltered solutions

- ▶ The unfiltered solutions show a much lower error level for the LRI than KBR. This is reasonable, because most noise is in the higher degrees which are more accurate from the LRI
- ▶ The spatial errors for the bigger pendulum angles are lower for all cases than for the Bender configuration, especially for LRI and the bigger background model errors



Conclusions

Simulation Study

- ▶ Bigger pendulum angle configurations (30° , ..., 75°) highly increase quality of GFR solutions compared to GRACE-like type, but for the very low degrees
- ▶ Bender configuration is just better for the very low degree coefficients
- ▶ With bigger pendulum angles higher background model errors are better compensated, especially for KBR
- ▶ The GRACE-like scenario does not benefit from the LRI, the Bender constellation just slightly benefits from the LRI, for the pendulum scenarios the LRI distinctly improves the higher degree coefficients
- ▶ For the shortest mean satellite distance of 120 km for all cases the results are worse over the whole spectrum, especially the higher and very low degrees
- ▶ The higher mean satellite distance reduces errors slightly, especially in the higher degrees and for KBR. This is observed for the pendulum and Bender configurations
- ▶ To fully exploit the pendulum configuration, an optimized processing or additional data to reduce the low degree errors might be advantageous
- ▶ Maybe a Bender configuration with one pair in a pendulum configuration might be interesting for further investigation



Conclusions

Practical Considerations/ Remarks

- ▶ Especially for the high pendulum angles, the relative velocities are comparably high, which causes problems to the current LRI system
- ▶ High pendulum angles also demand more attitude control effort and maybe an optimized satellite geometry
- ▶ Compared to that, the Bender constellation has about TRL 9, practically being a copy of two GRACE/ GRACE-FO missions

Mean satellite distance

- ▶ Even though the bigger mean satellite distances gives slightly better results, its implementation is more challenging in terms of ranging system, and also the demands on the attitude control are increasing with bigger distances
- ▶ Maybe a Bender configuration with one pair in a pendulum configuration might be interesting for further investigation



Thank you for your attention!

► **Comments/ Questions?**

Welcome at any time → **florian.woeske@zarm.uni-bremen.de**

Or in Session G4.2, Friday, 30 April, 11:45–15:00 (CEST)

