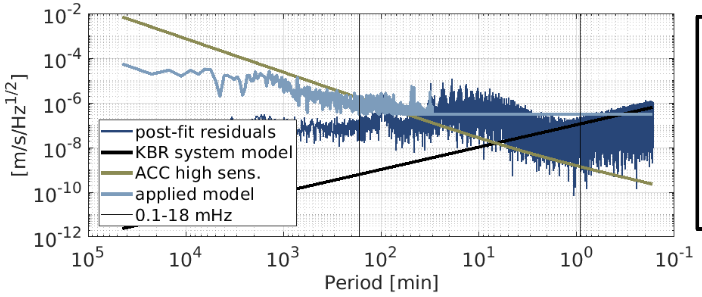
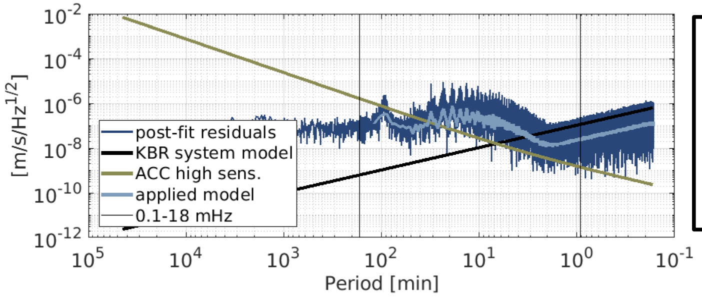
Martin Lasser
Ulrich Meyer
Daniel Arnold
Adrian Jäggi

Comparison of empirical noise models for GRACE Follow-On derived with the Celestial Mechanics Approach

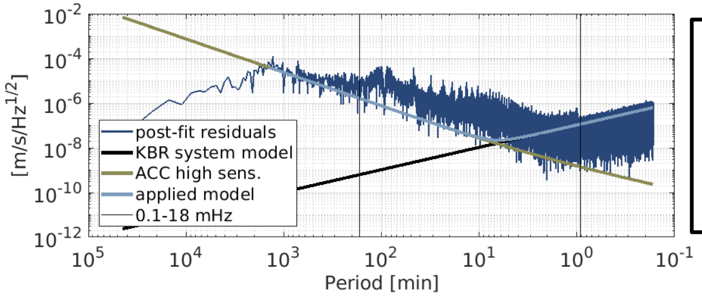
EGU General Assembly 2021



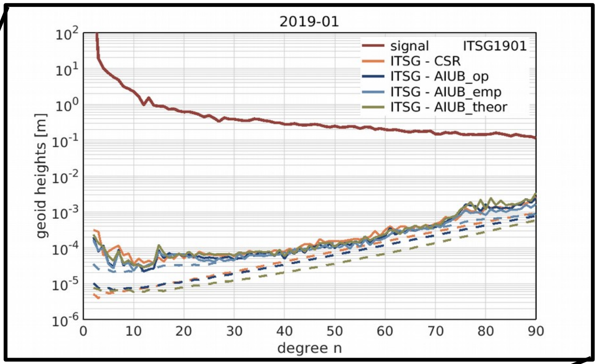
15 min piecewise-constant accelerations
«op»

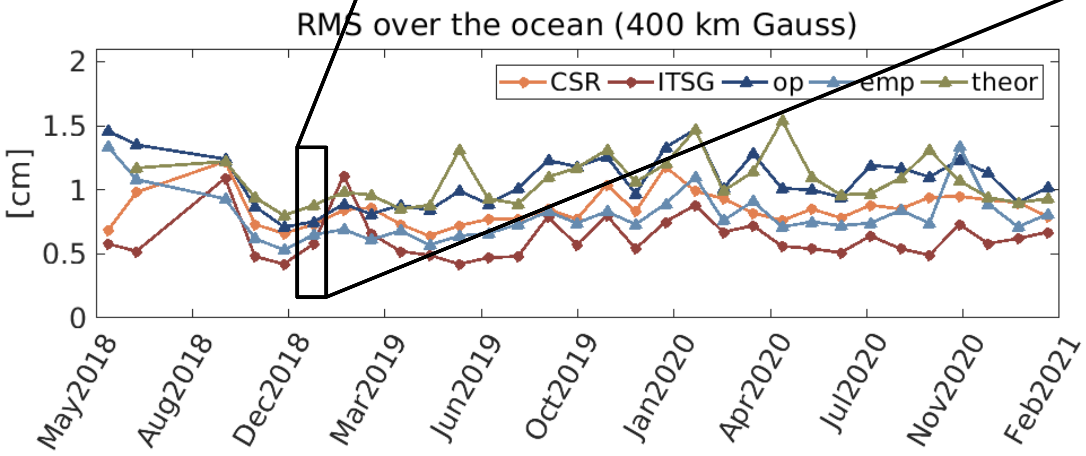


empirical noise model based on post-fit residuals
«emp»



theoretical noise models for KBRR and ACC [Kim, 2000]
«theor»





CONCLUSIONS

- Best performance for «emp»
- No severe degradation for «theor»
- Smallest residuals in «op»

Astronomical Institute, University of Bern AIUB

Comparison of empirical noise models for GRACE Follow-On derived with the Celestial Mechanics Approach

Martin Lasser, Ulrich Meyer, Daniel Arnold, Adrian Jäggi

Astronomical Institute, University of Bern, Switzerland

EGU General Assembly 2021
Apr. 19-30, 2021
Online

Introduction

Correctly modelling the measurement noise is crucial for recovering high quality gravity fields:

- AIUB_op («op»): piecewise-constant accelerations (PCA)
- AIUB_emp («emp»): empirical noise model based on post-fit residuals
- AIUB_theor («theor»): theoretical noise models for GRACE [Kim, 2000]

Introduction

Correctly modelling the measurement noise is crucial for recovering high quality gravity fields:

- AIUB_op («op»): piecewise-constant accelerations (PCA)
- AIUB_emp («emp»): empirical noise model based on post-fit residuals
- AIUB_theor («theor»): theoretical noise models for GRACE [Kim, 2000]

Celestial Mechnaics Approach (CMA) with

Gravity field	Internal AIUB static GRACE field
Astromomic bodies	JPL DE421 (all planets + Pluto)
Mean pole	Linear
Solid Earth tides, Solid Earth pole tides, Relativistic effects	IERS2010
Ocean tides	FES2014b (+ admittances from ITSG)
Ocean pole tides	Desai
Atmospheric tides, Atmospheric & oeanic dealiasing	AOD RL06
Non-conservative forces	Accelerometer L1b (from ITSG)

Noise models – piecewise-constant accelerations

«op»

basic parametrisation:
- initial conditions 2x(6)
- accelerometer bias 2x(3)
- accelermeter scaling 2x(3)

parameters per arc 24

noise model:
- KBRR white noise 0.3 µm/s
- 15 min PCA per satellite in
  - radial 2x(96)
  - along track 2x(96)
  - Cross-track 2x(96)

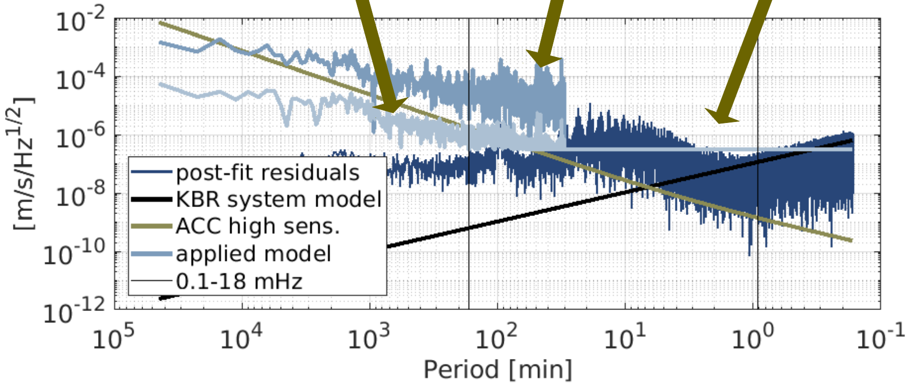
parameters per arc 576

in daily arcs (30 days):
- 18000 parameter,
- 17280 for the noise model
- + gravity field

PCA SUM
Constrained: $3x10^{-10}$ m/s²

PCA DIFF
constrained: $3x10^{-11}$ m/s²

white noise 0.3 µm/s



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Noise models – piecewise-constant accelerations

«op»

basic parametrisation:
- initial conditions 2x(6)
-
-

PCA SUM

no
-
-

orbit transformation (described in Beutler et al. 2010):

instead of estimating parameters for GF1 & GF2
transform orbit parameters to:

$$\frac{GF1+GF2}{2}$$ → SUM: referring to the mean point in space between GF1 & GF2 (driven by GPS)

$$\frac{GF1-GF2}{2}$$ → DIFF: referring to the difference between GF1 & GF2 (driven by K-band)

in daily arcs (30 days):
- 18000 parameter,
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PCA – performance

«op»

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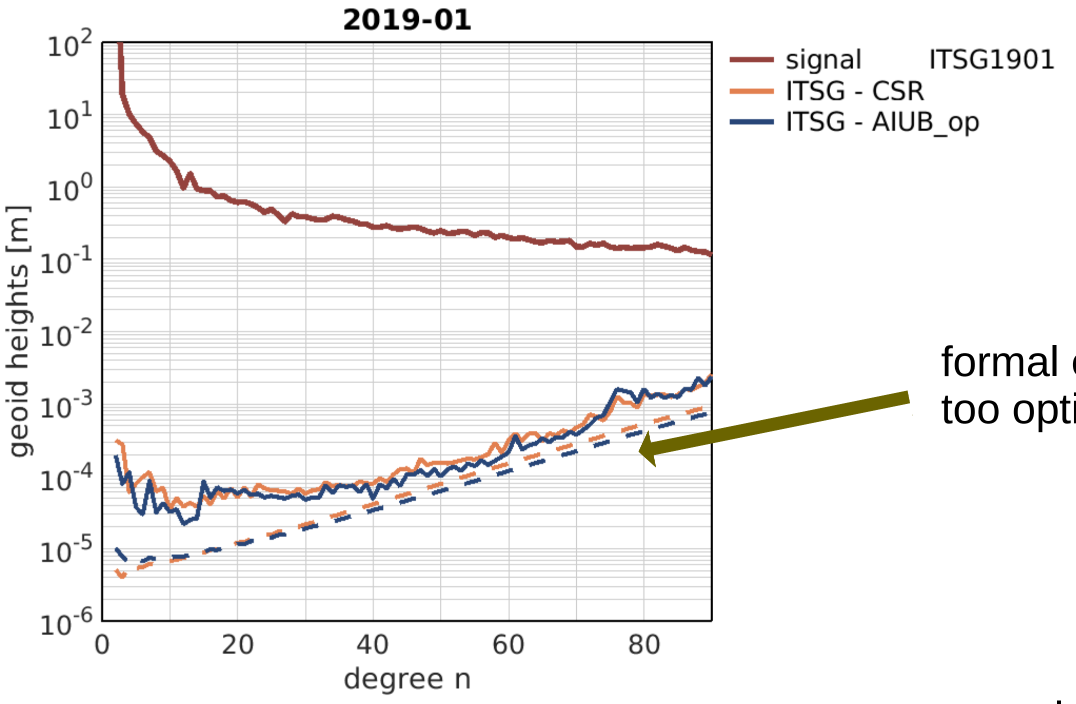
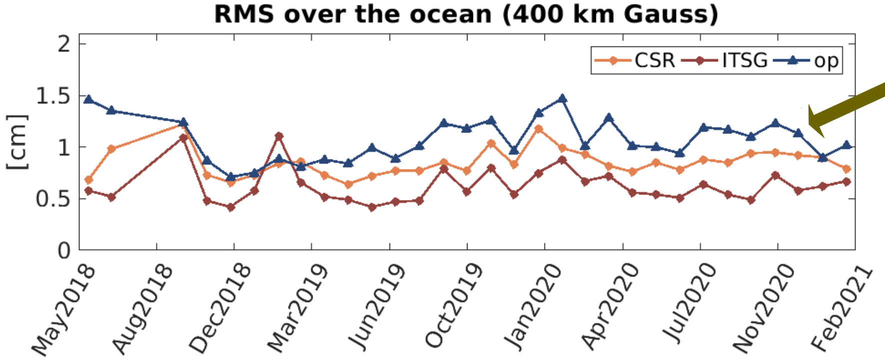


formal errors too optimistic



solution quality acceptable with room for improvement

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PCA – conclusions

«op»

basic parametrisation:

• initial conditions	2x(6)
• accelerometer bias	2x(3)
• accelermeter scaling	2x(3)
parameters per arc	24

noise model:

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- 15 min PCA per satellite in

➔ radial	2x(96)
➔ along track	2x(96)
➔ Cross-track	2x(96)
parameters per arc	576

in daily arcs (30 days):

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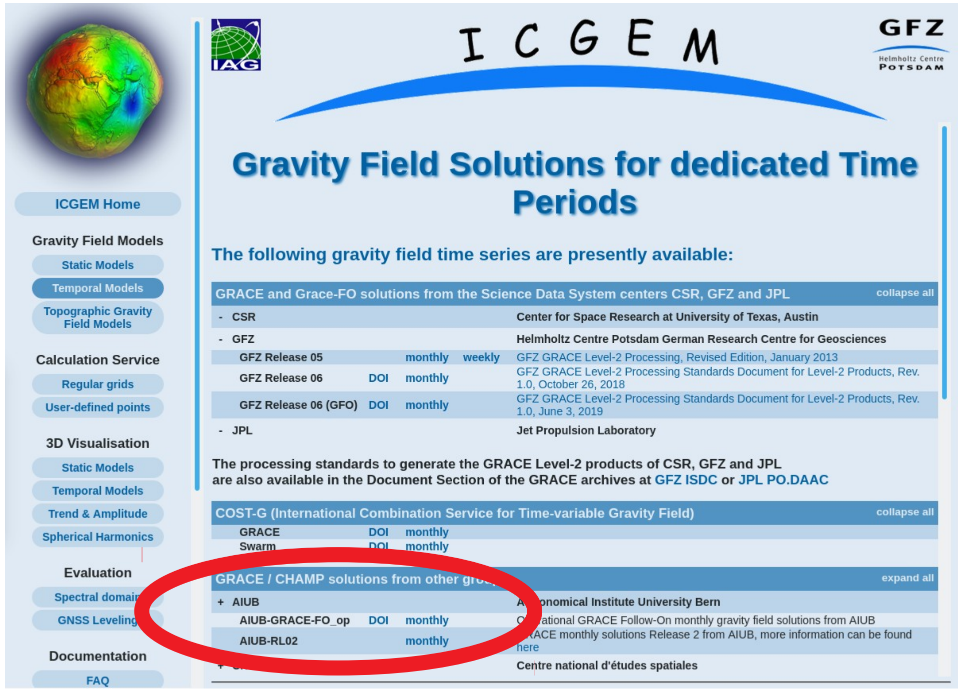
- + gravity field

- «classical» Celestial Mechanics Approach
- no iterations required
- published at ICGEM



- extension of parameter space demands higher memory
- and CPU capacity (inversion)
- constraints need to be determined (manually, VCE)

Noise models – from post-fit residuals

«emp»

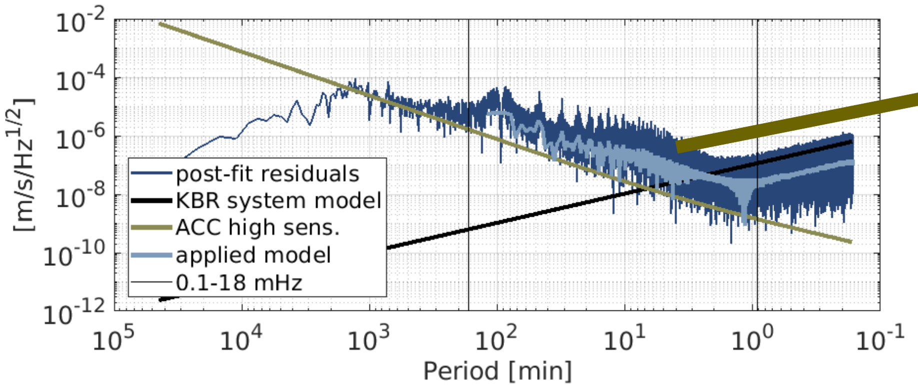
basic parametrisation:
- initial conditions 2x(6)
- accelerometer bias 2x(3)
- accelermeter scaling 2x(3)

parameters per arc 24

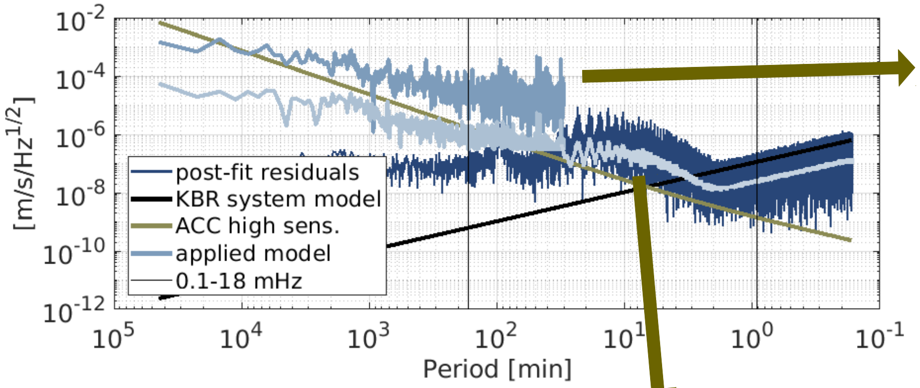
noise model:
- empirical covariances based on post-fit residuals

no additional parameters
➔ requires iterative procedure
➔ assumption of stationarity

in daily arcs (30 days):
- 720 parameters
- + gravity field



empirical model applied for 3 hours



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parameters per arc 576

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Empirical covariances

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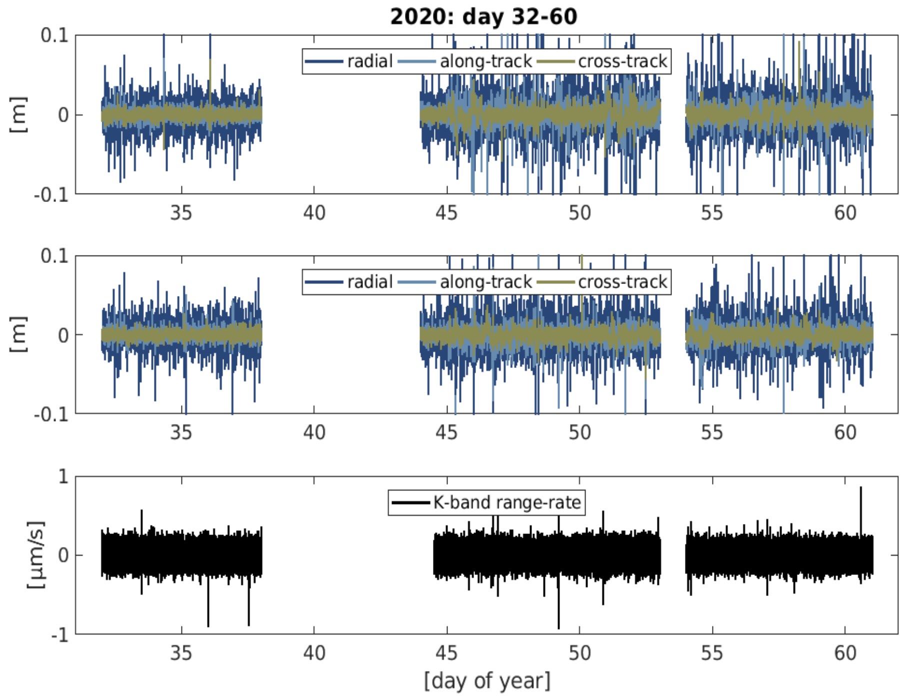

auto/cross-correlation

$\mathbf{P}_{KIN,GF1}$

$\mathbf{P}_{KIN,GF2}$

$\mathbf{P}_{Kb}$

Empirical covariances

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parameters per arc 24

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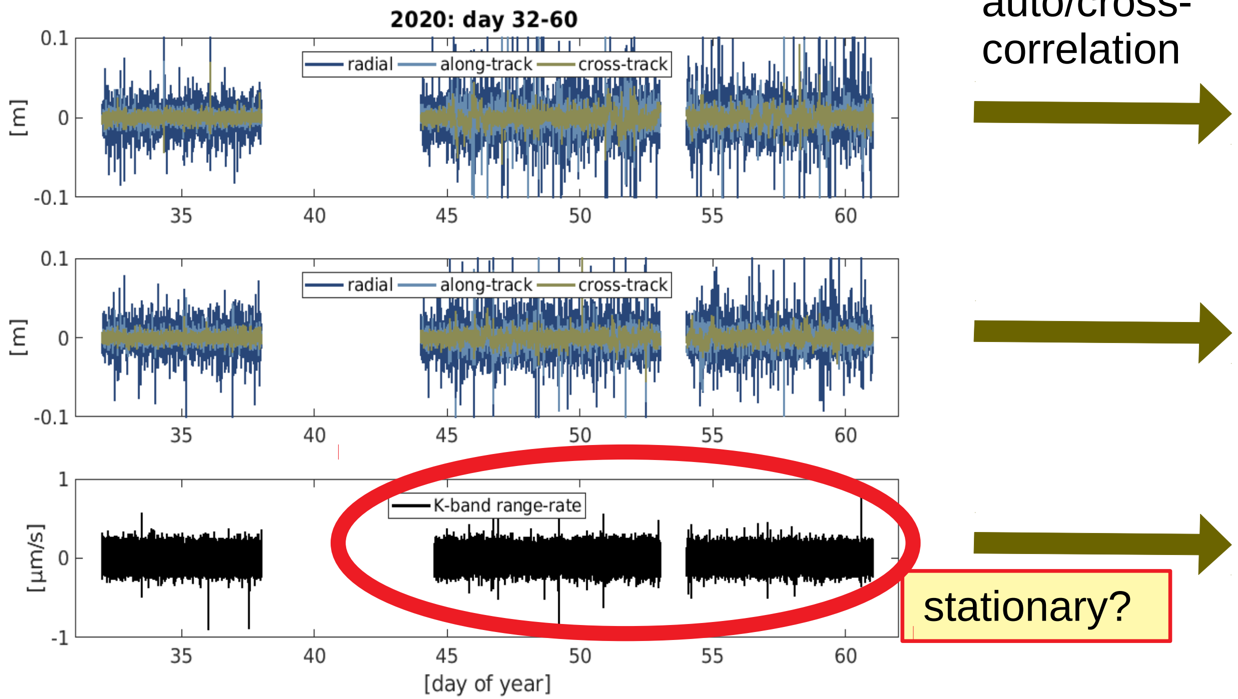
«emp»



$P_{KIN,GF1}$

$P_{KIN,GF2}$

P_{Kb}

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Empirical covariance function

«emp»

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parameters per arc	24

noise model:
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in daily arcs (30 days):
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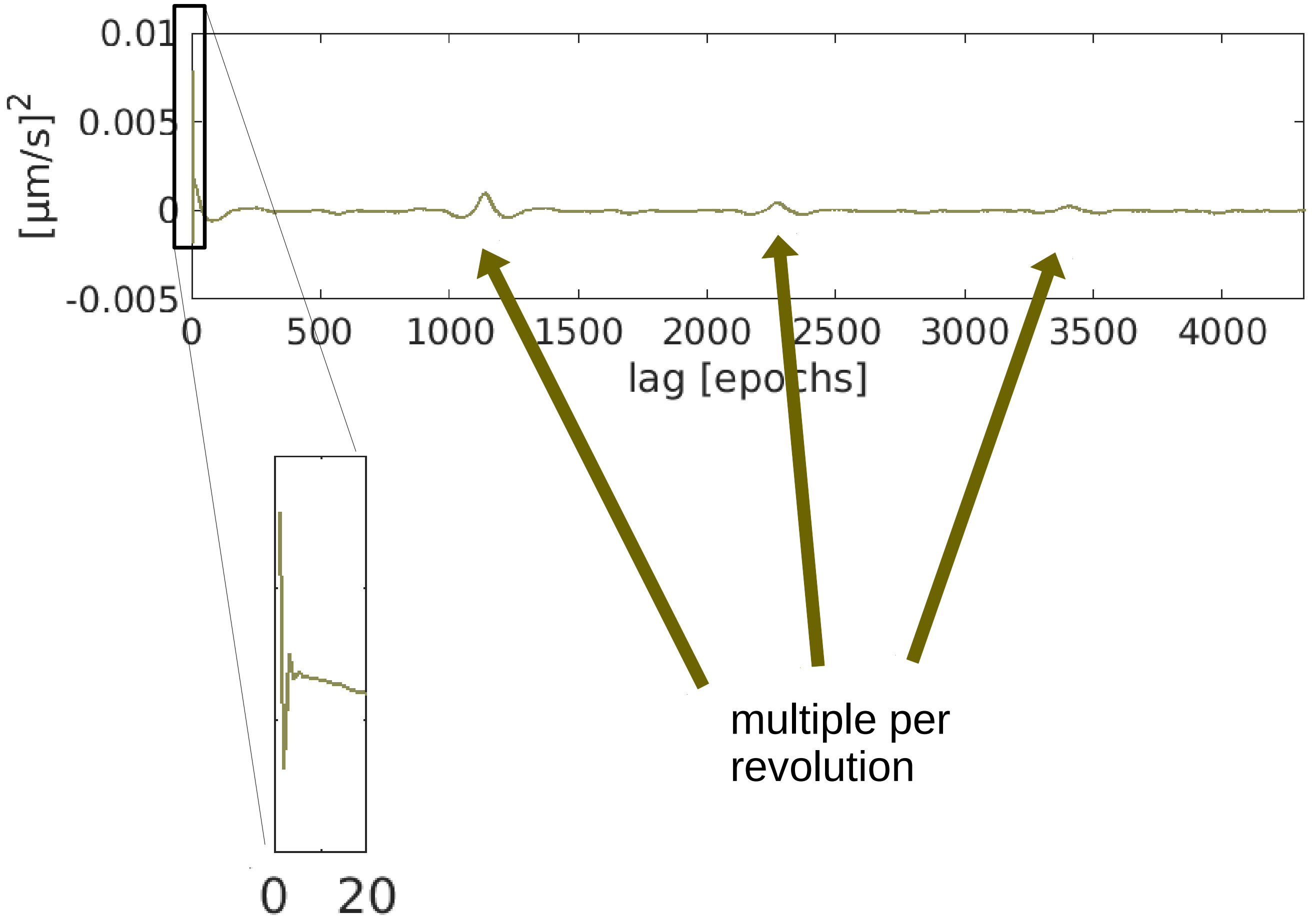

Empirical covariances - performance

«emp»

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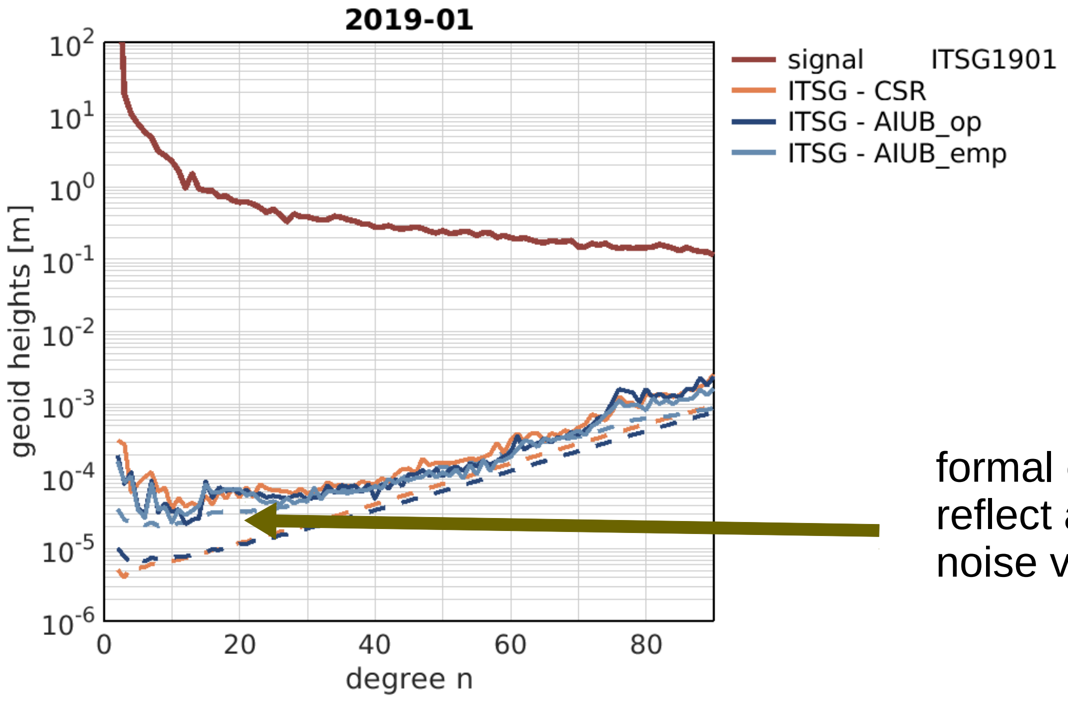
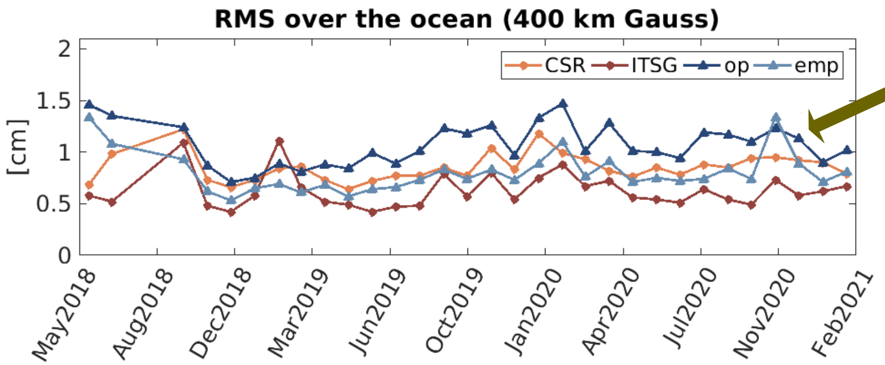


formal errors reflect assessed noise very well



clear improvement of solution quality

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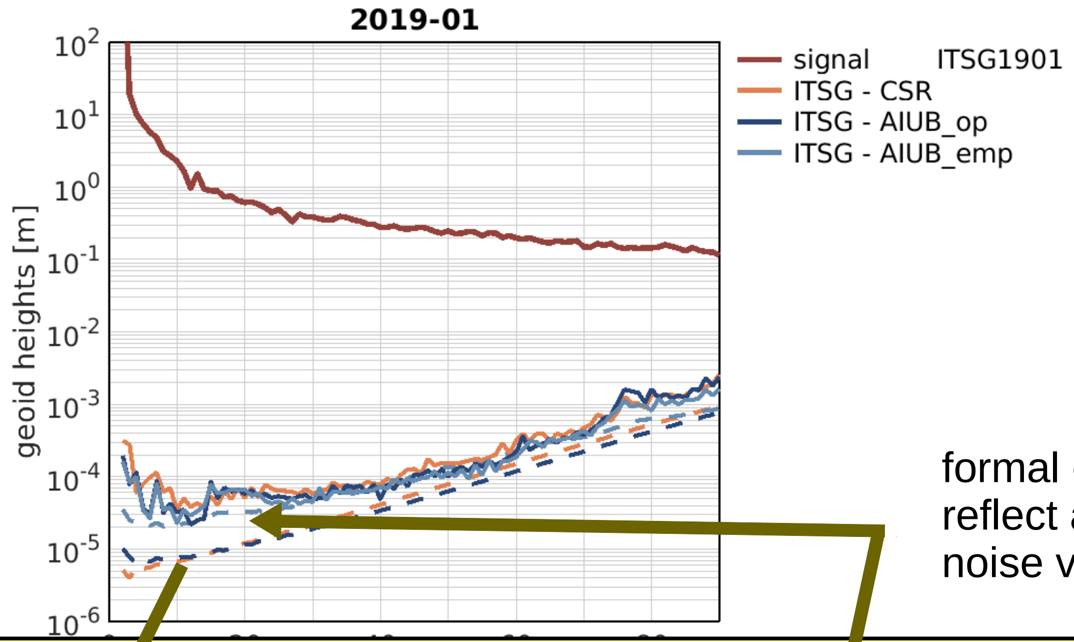
no additional parameters

➔ requires

➔ assumpt

in daily arc

- 720 para
- + gravity



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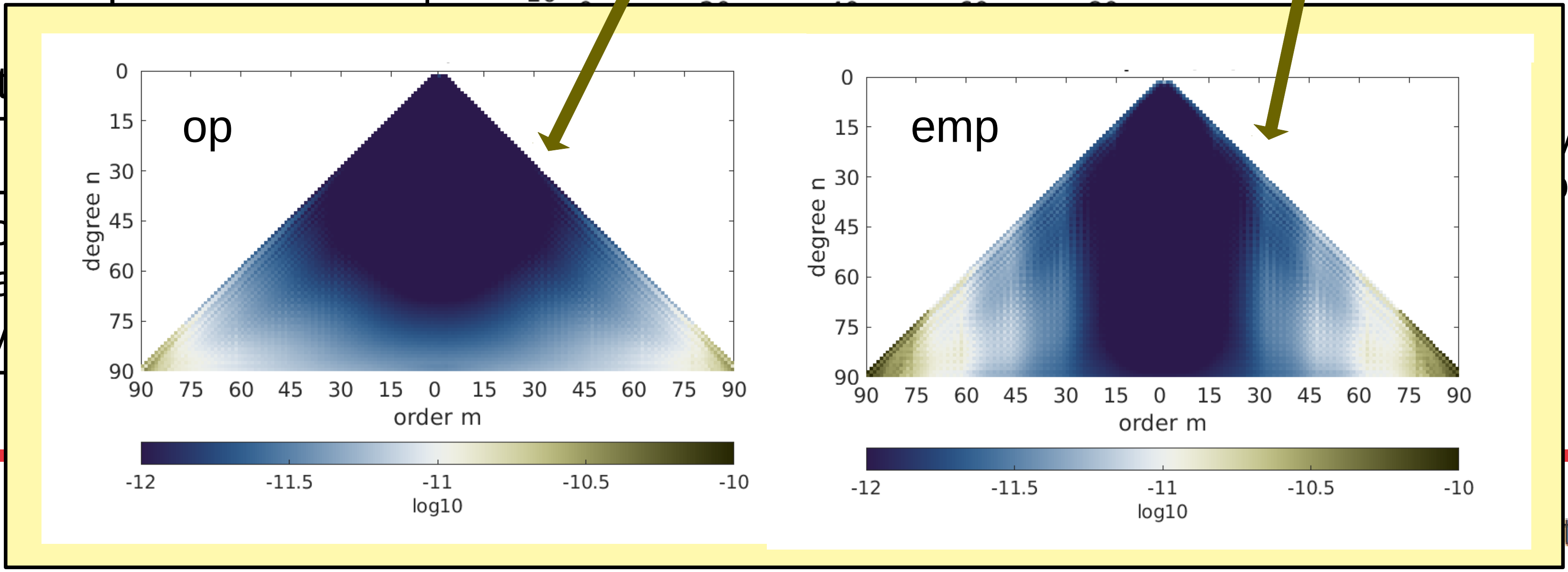

...vement of

...n quality

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Empirical covariances - conclusions

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parameters per arc 24

noise model:
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no additional parameters
→ requires iterative procedure
→ assumption of stationarity

in daily arcs (30 days):
- 720 parameters
- + gravity field

- possible on any (stationary) residuals time series
- additional parameters can be reduced as stationary behaviour can be absorbed
- formal errors become much more realistic and show resonance orders (if correlation length > 3 h)
- no constraints needed
- no/few a priori knowledge needed

- iterations required (might be time consuming)
- memory consumption and inversion time dependent on length of auto/cross-correlation

Noise models – theoretical (pre-launch)

«theor»

basic parametrisation:
- initial conditions 2x(6)
- accelerometer bias 2x(3)
- accelermeter scaling 2x(3)

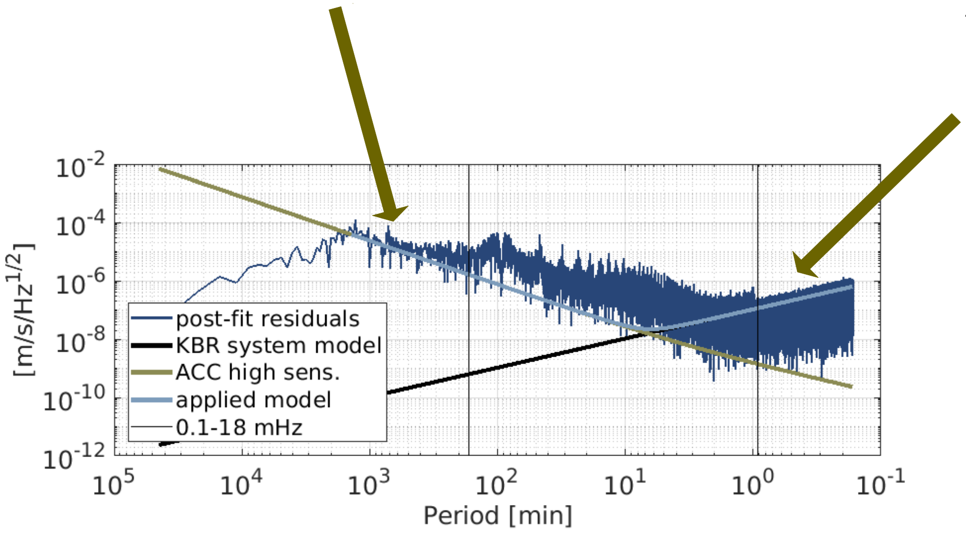
parameters per arc 24

noise model [Kim, 2000]:
- ACC high sensitivity axis
  $(1 + 0.005/f) \times 10^{-20}$ m/s²
- KBR white noise
  1 µm range
  (differentiation to KBRR)

in daily arcs (30 days):
- 720 parameters
- + gravity field

ACC noise (red noise):
PSD: $(1 + 0.005/f) \times 10^{-20}$ m/s²

ACC noise (violet noise):
1 µm range



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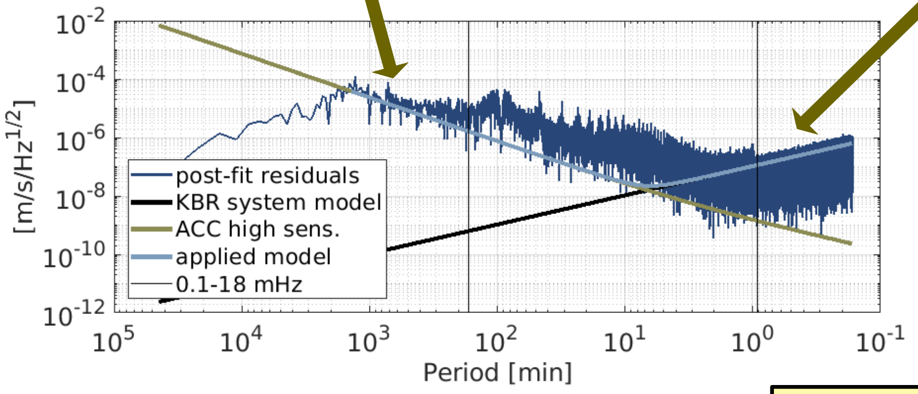

- coloured noise ~stationary
- sum at least jointly stationary

➔ Wiener-Khinchin theorem to derive auto-correlation from PSD

Theoretical (pre-launch) - performance

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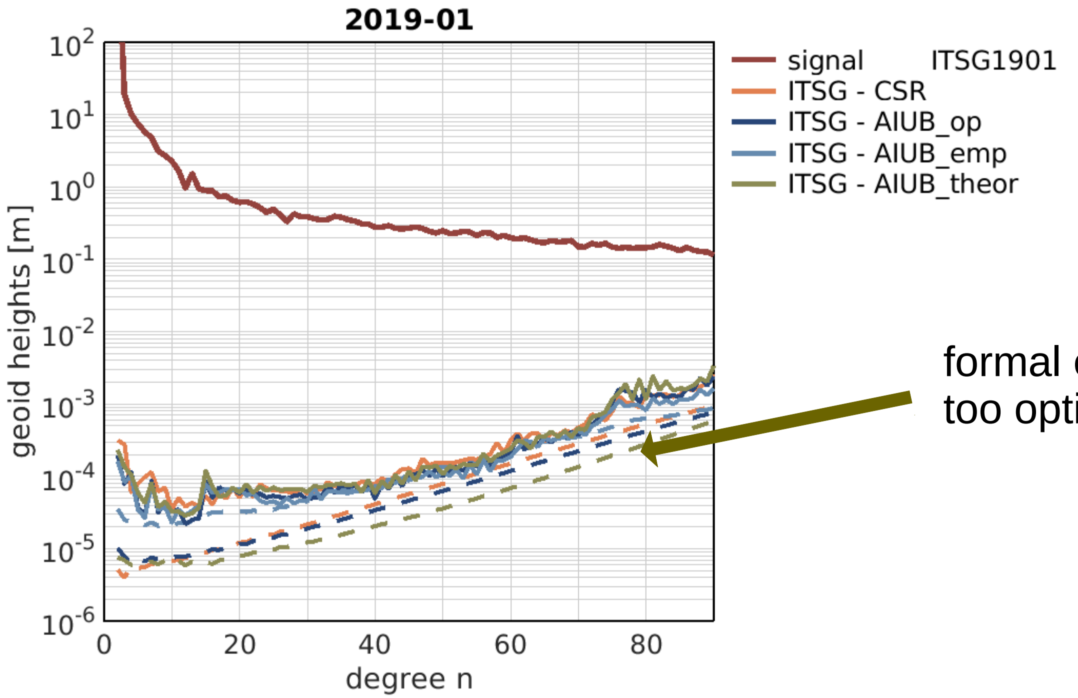

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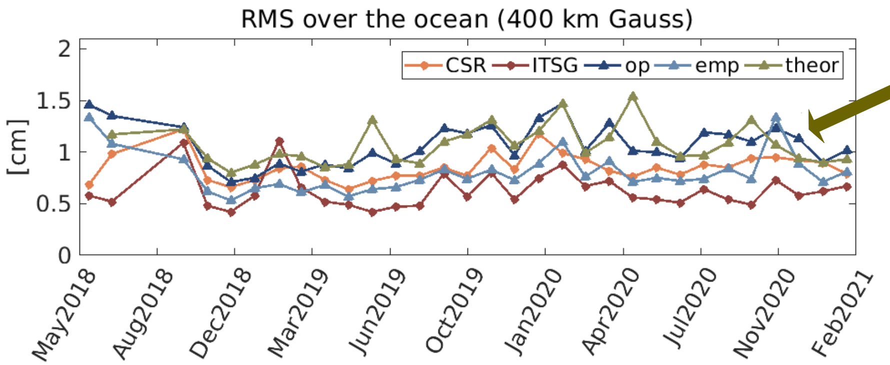

solution quality acceptable (!) with room for improvement

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  1 µm range
  (differentiation to KBRR)

in daily arcs (30 days):
- 720 parameters
- + gravity field

- based on priori knowledge
- additional parameters can be reduced
- provides a good solution in case observations act as a priori models state
- no constraints needed
- no iterations needed
- requirements on memory and CPU low

- might not reflect actual noise (e.g., without ACT from ITSG)
- formal errors too optimistic
- not all error sources included (e.g., backgorund models)

References

Beutler, G., Jäggi, A., Mervart, L. and Meyer, U. [2010]: The celestial mechanics approach: theoretical foundations. Journal of Geodesy, vol. 84(10), pp. 605-624. https://doi.org/10.1007/s00190-010-0401-7

Kim, J. [2000]: Simulation Study of A Low-Low Satellite-to-Satellite Tracking Mission, PhD-Thesis, Center for Space and Research, Texas, USA.
http://granite.phys.s.u-tokyo.ac.jp/ando/GRACE/Kim_dissertation.pdf

Lasser, M., Meyer, U., Arnold, D. and Jäggi, A. [2020]: AIUB-GRACE-FO-operational - Operational GRACE Follow-On monthly gravity field solutions. https://doi.org/10.5880/ICGEM.2020.001

Mayer-Gürr, T., Behzadpur, S., Ellmer, M., Kvas, A., Klinger, B., Strasser, S. and Zehentner, N. [2018]: ITSG-Grace2018 - Monthly, Daily and Static Gravity Field Solutions from GRACE.
https://doi.org/10.5880/ICGEM.2018.003

NASA Jet Propulsion Laboratory (JPL) [2019]: GRACE-FO Monthly Geopotential Spherical Harmonics CSR Release 6.0. https://doi.org/10.5067/GFL20-MC060