# Cold atom interferometer accelerometry for future satellite gravimetry missions

**Manuel Schilling[1,2], Annike Knabe[2], Hu Wu[2], Jürgen Müller[2,1]**

[1]Institute for Satellite Geodesy and Inertial Sensing, DLR, Hannover, Germany

[2]Institute of Geodesy, Leibniz University Hannover, Germany

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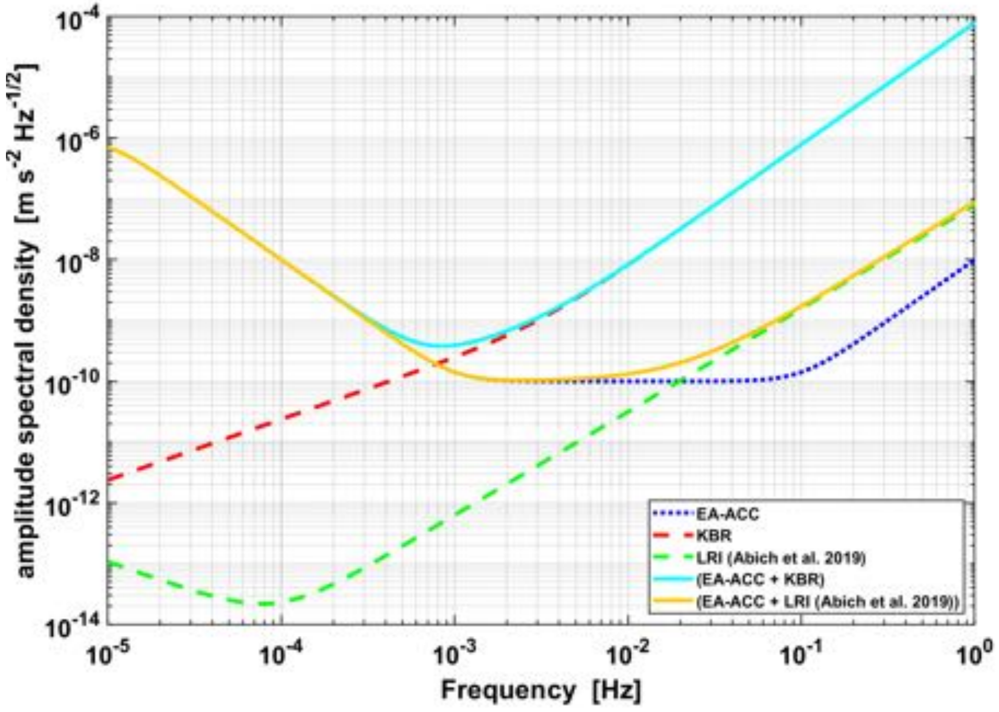
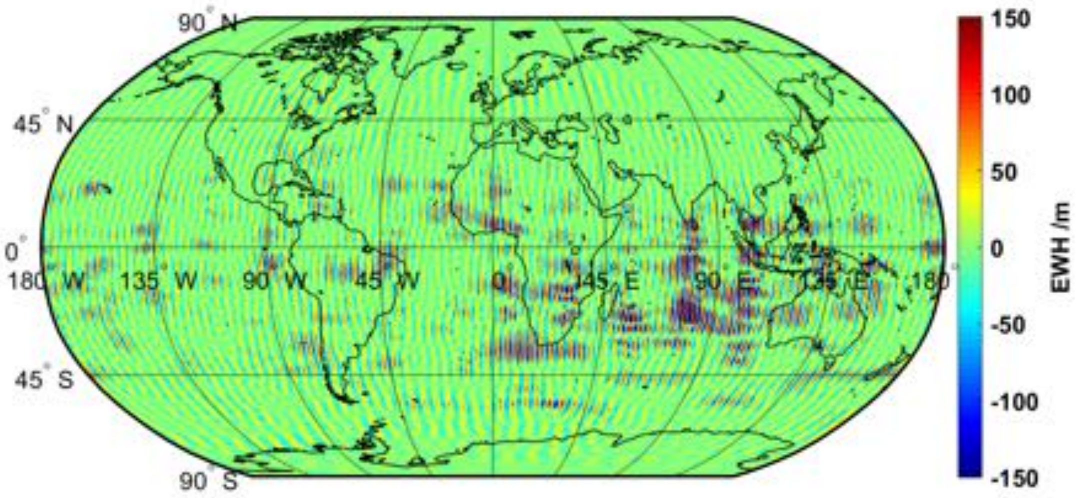
# Motivation

Transition GRACE → GRACE-FO
- Laser ranging interferometer
- Further innovation of LRI provides only little gain

Expected gain of improved accelerometers
- Exploit potential of LRI
- Reduction of systematic effects
- Improved low d/o coefficients

Cold atom interferometer
- No or very low drift
- Very low scale factor uncertainty

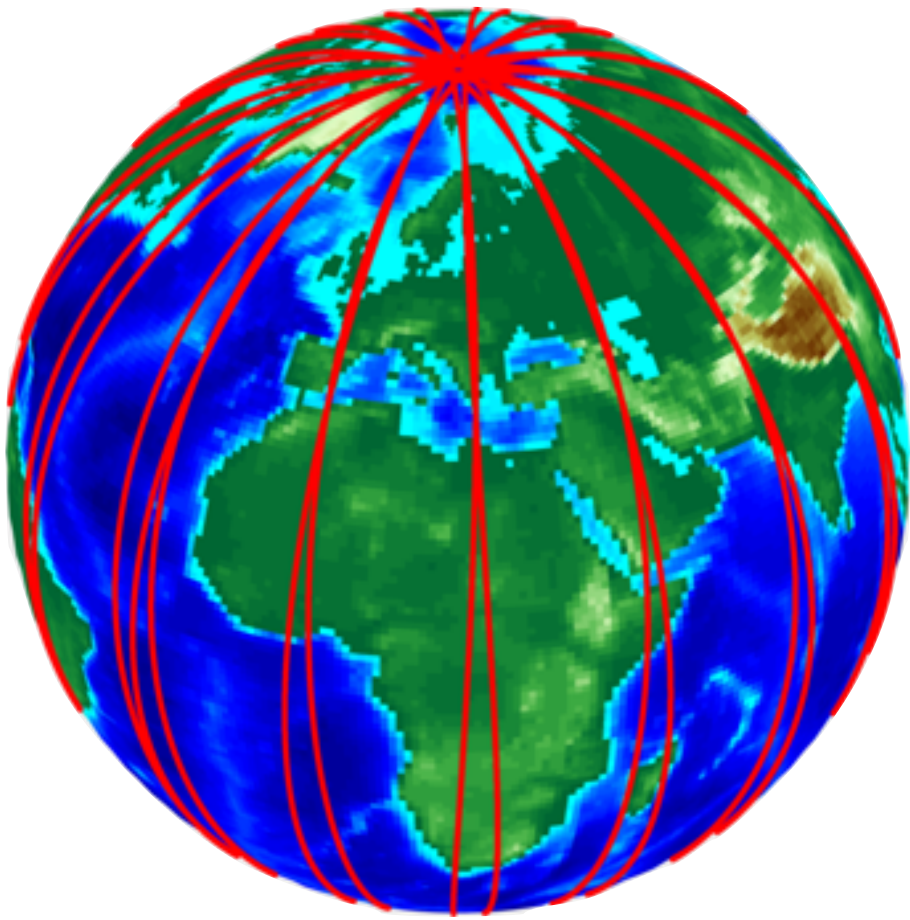


# Simulation environment

This presentation: **GRACE-FO type scenarios**

1. Input gravity field and non-gravitational accelerations
   → satellite orbits (XHPS: Wöske et al. 2019)
2. Error free observations
   → range accelerations in line of sight
3. Introduction of noise (ranging, ACC, attitude, AOD,…)
   → noisy observations
4. Gravity field recovery
5. Comparison with input gravity field



Gravity field: Eigen-6c4 Förste et al. 2014 LRI: Abich et al. 2019
AOD noise: AOD1B RL6 Dobslaw et al. 2017

# Atom interferometry concept

Cold atoms as test masses in an interferometer

Leading order phase shift $\Delta\Phi$

$$\Delta\Phi = \mathbf{k}_{\text{eff}} \cdot \mathbf{a}\, T^2$$

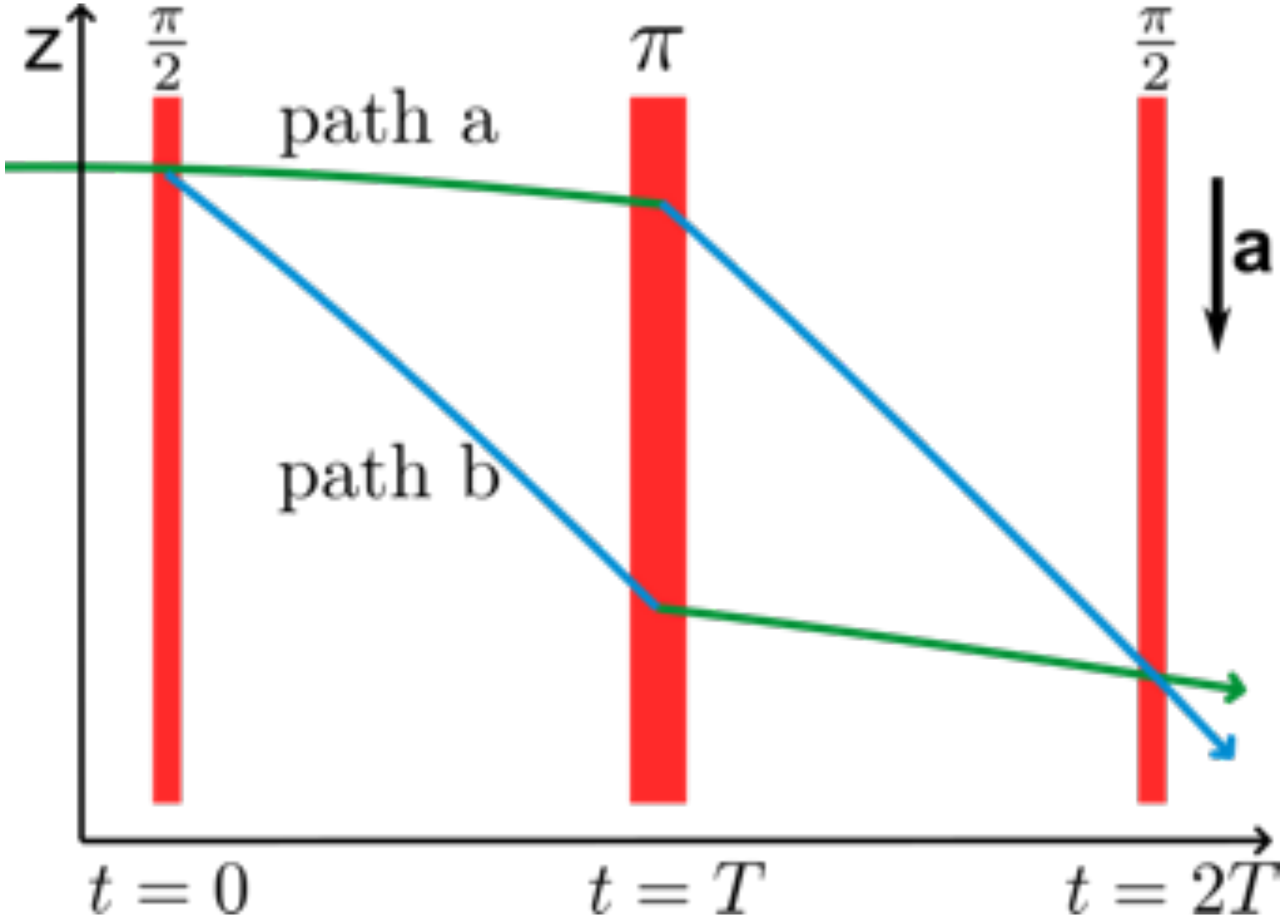
One axis, e.g. along track: $\mathbf{k}_{\text{eff}} || \mathbf{a}$

$$\Delta\Phi = k_{\text{eff}} \left( a - \frac{\alpha}{k_{\text{eff}}} \right) T^2$$

Frequency chirp $\alpha$ (partly) compensates acceleration of atoms

Measurement: population *P* of atoms per state

$$P_{|e\rangle} = \frac{1}{2} \left(1 - \cos \Delta\Phi\right)$$




Mach-Zehnder light-pulse atom interferometer

# Hardware developments for terrestrial and space applications

Terrestrial gravimetry

- GAIN (HUB), CAG (LNE-SYRTE)
- Commercial product: Muquans AQG
- BEC atom chip gravimeter QG1 (LUH)
- Ship-/Airborne gravimetry (ONERA)

Other Applications

- Fundamental physics, gravitational wave detection
- Rotation sensing, navigation

Experiments and demonstrators for space

- Sounding-rocket experiment [Becker et al. 2018]
  MAIUS: First Bose-Einstein Condensate in Space
- Cold Atom Laboratory (CAL)
  Currently on International Space Station
- Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL)
  Future experiment for the ISS
- Initiatives for CAI-ACC demonstrator on satellite
- ONERA: hybrid-ACC study

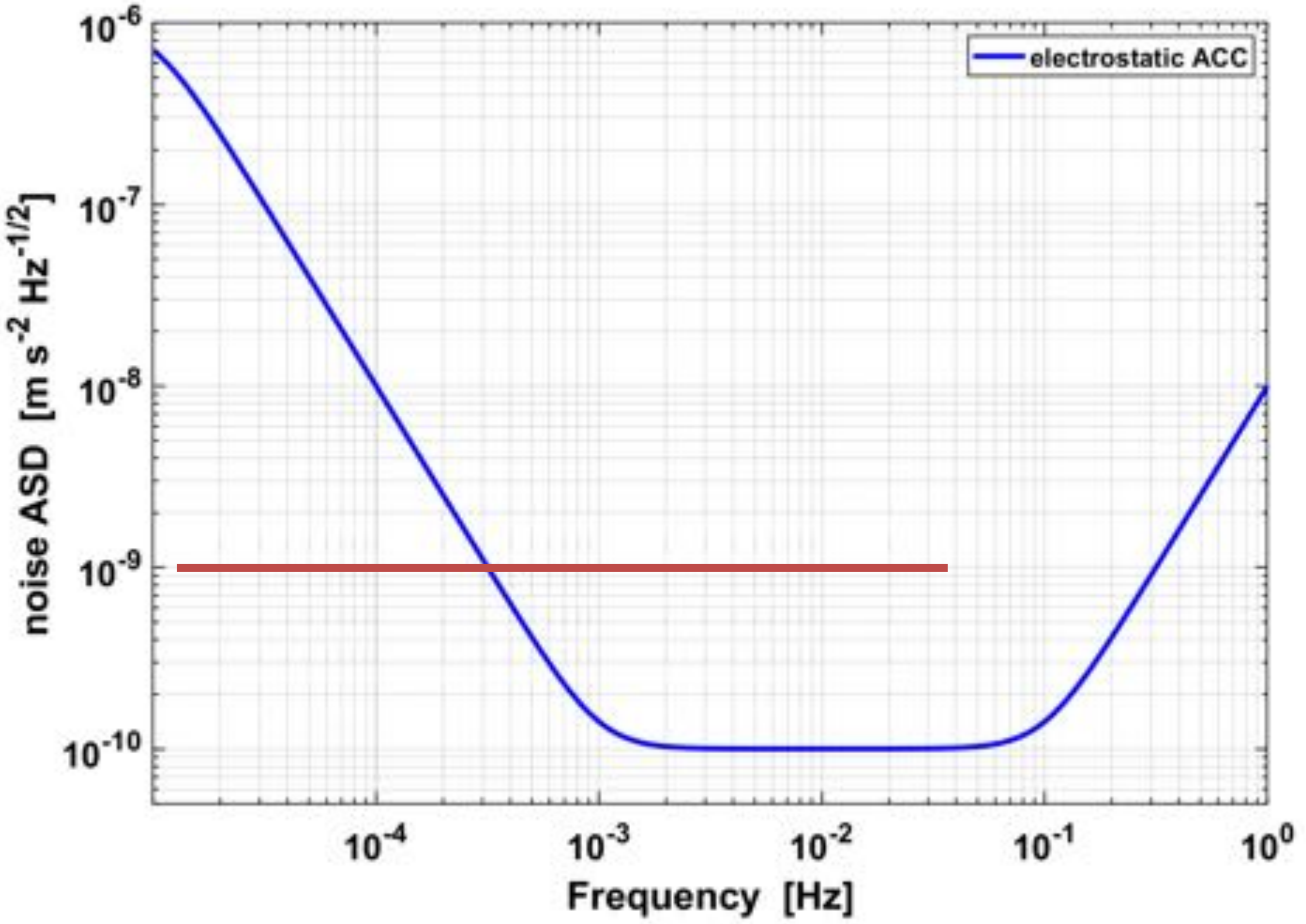
# Improving the accelerometer with CAI

Electrostatic ACC GRACE(-FO)

- Flat ASD in measurement bandwidth
  → limit non-gravitational forces
- Low frequency $(< 10^{-3}\mathrm{Hz})$ drift
  → limit low d/o coefficients

Adding CAI to form a hybrid-ACC

- White noise $10^{-9}\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$
  e.g. performance of GAIN [Freier2017]
- Improvement in lower frequencies
- Is white noise a realistic assumption?




GRACE ACC noise model sensitive axes [Flury et al. 2008]

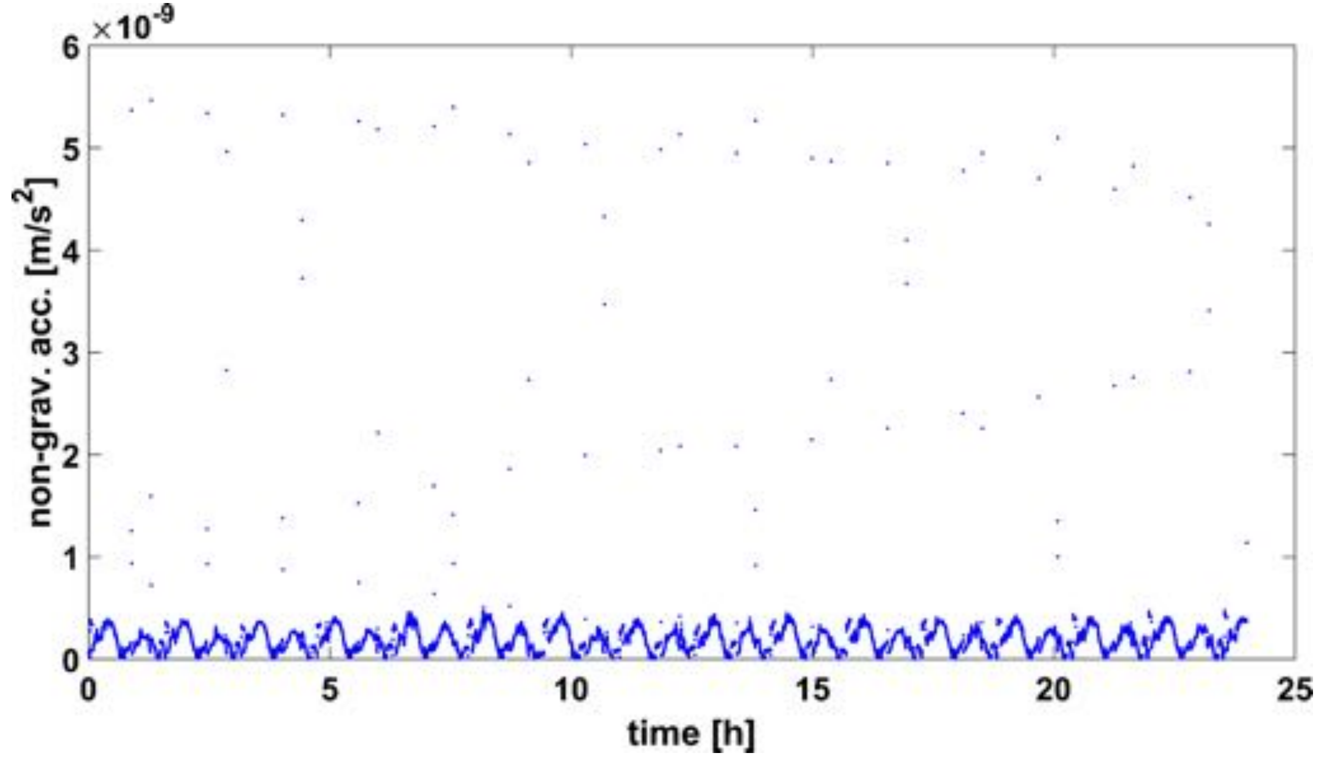
# Improving the accelerometer with CAI

Combining a hybrid-ACC

- Data rate EA >> 1Hz
- CAI sensitivity increases with time

$$\Delta\Phi = \mathbf{k}_{\text{eff}} \cdot \mathbf{a}\, T^2$$

- CAI measurement of several seconds
  → Change of non grav. force **a** during T
  → Rotation of satellite




Variation (min-max) of non gravitational acceleration along track in GRACE orbit height over 12s

# Improving the accelerometer with CAI

Combining a hybrid-ACC

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$$\Delta\Phi = \mathbf{k}_{\text{eff}} \cdot \mathbf{a}\, T^2$$

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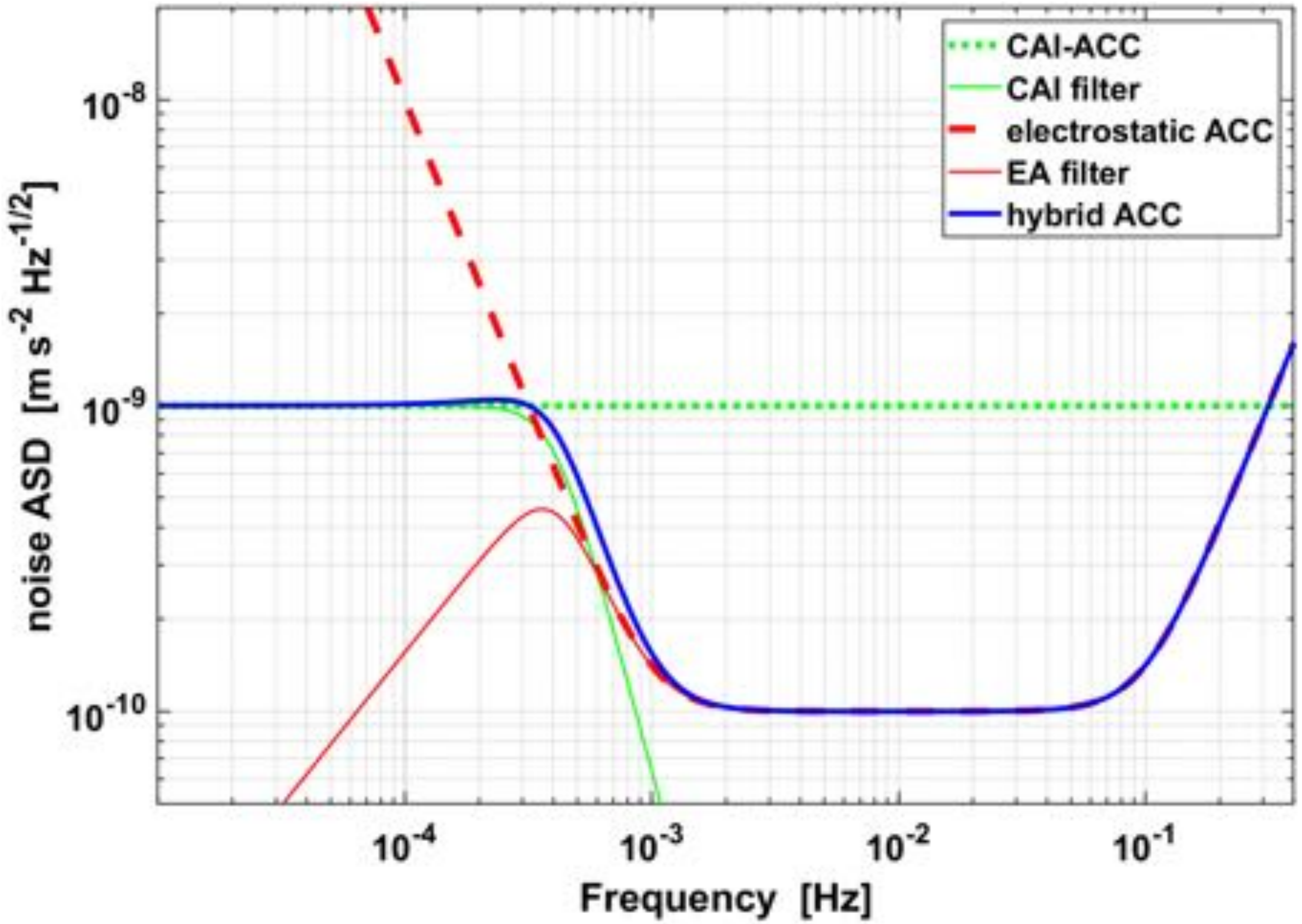
Filter strategy

- Low-/Highpass filter
- Kalman filter
- Suitable for drag-free control?

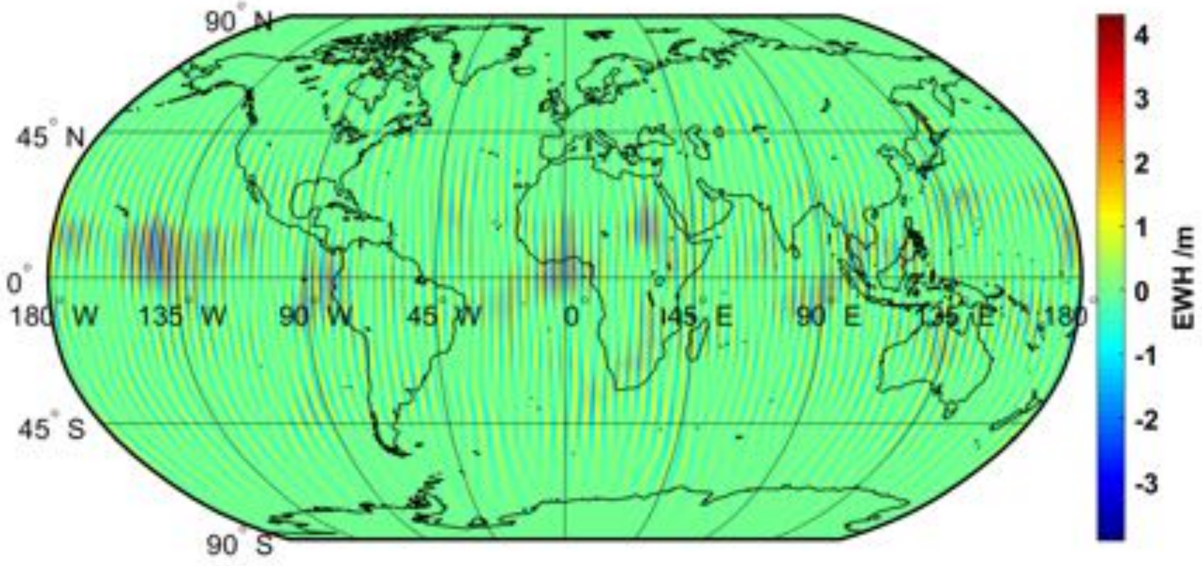


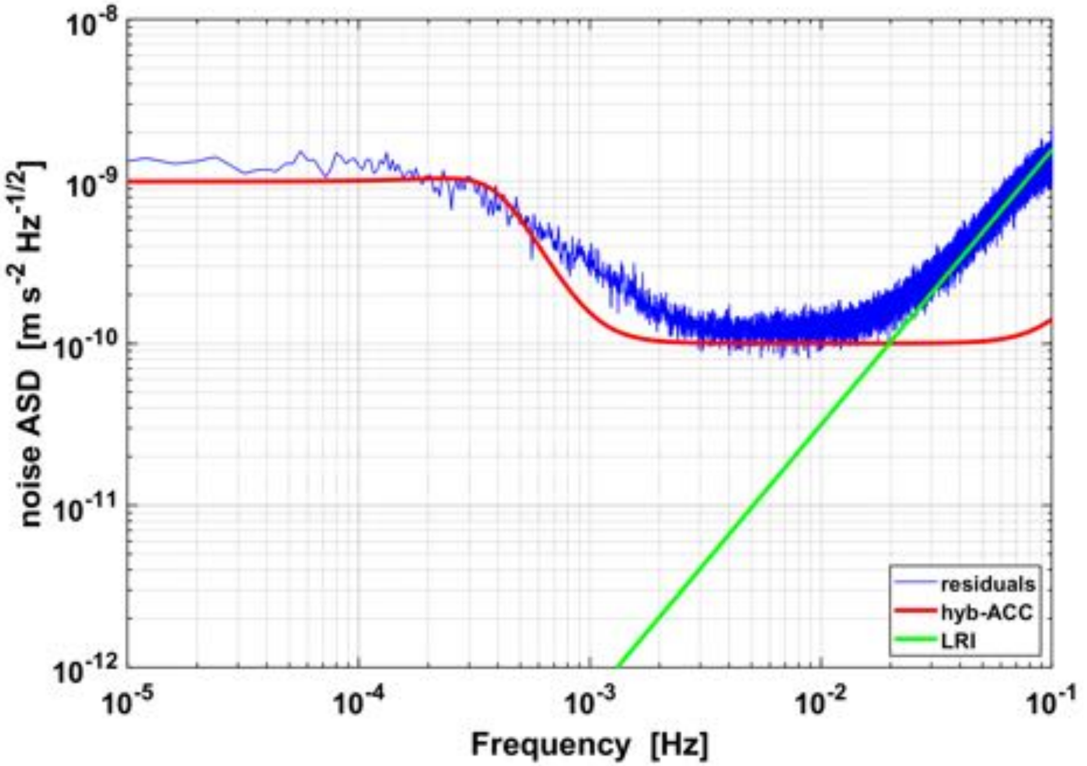

Combination of electrostatic and CAI- ACC

# Scenario 1

| | Electrostatic ACC | CAI-ACC |
|---|---|---|
| **1** | **$10^{-10}$ m $s^{-2}$ $Hz^{-1/2}$** | **$10^{-9}$ m $s^{-2}$ $Hz^{-1/2}$** |
| 2 | $10^{-11}$ m $s^{-2}$ $Hz^{-1/2}$ | $10^{-9}$ m $s^{-2}$ $Hz^{-1/2}$ |
| 3 | $10^{-12}$ m $s^{-2}$ $Hz^{-1/2}$ | $10^{-11}$ m $s^{-2}$ $Hz^{-1/2}$ |

- Gravity Field Recovery for d/o 90
- CAI-ACC only in along track direction
- Post fit residuals: range accelerations



# Scenario 2

| | Electrostatic ACC | CAI-ACC |
|---|---|---|
| 1 | $10^{-10}$ m s$^{-2}$ Hz$^{-1/2}$ | $10^{-9}$ m s$^{-2}$ Hz$^{-1/2}$ |
| **2** | **$10^{-11}$ m s$^{-2}$ Hz$^{-1/2}$** | **$10^{-9}$ m s$^{-2}$ Hz$^{-1/2}$** |
| 3 | $10^{-12}$ m s$^{-2}$ Hz$^{-1/2}$ | $10^{-11}$ m s$^{-2}$ Hz$^{-1/2}$ |

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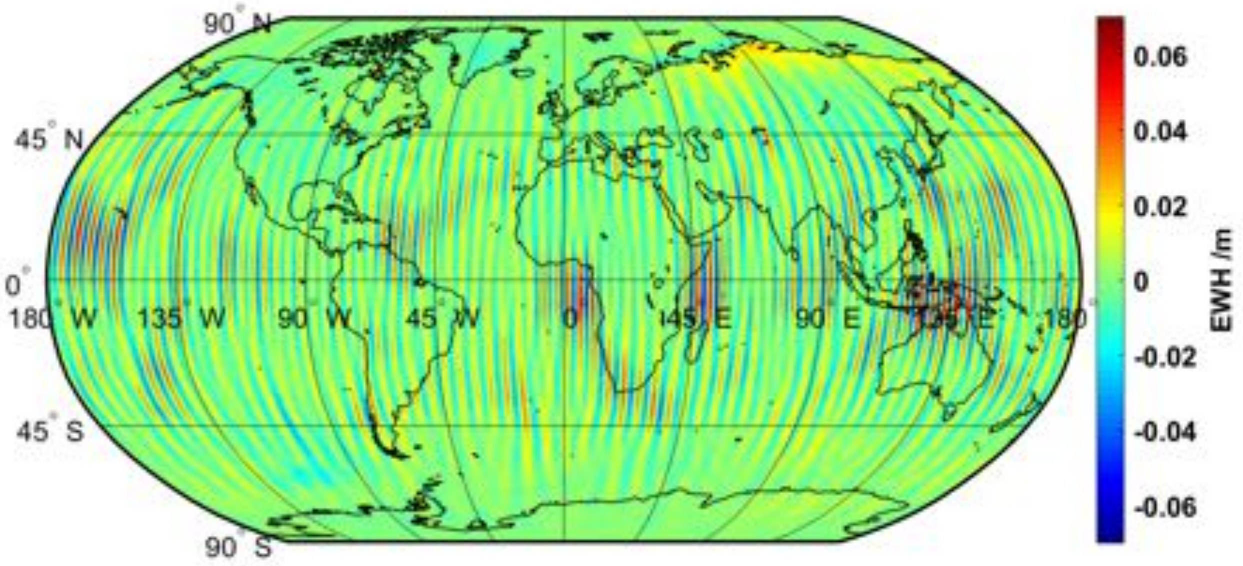
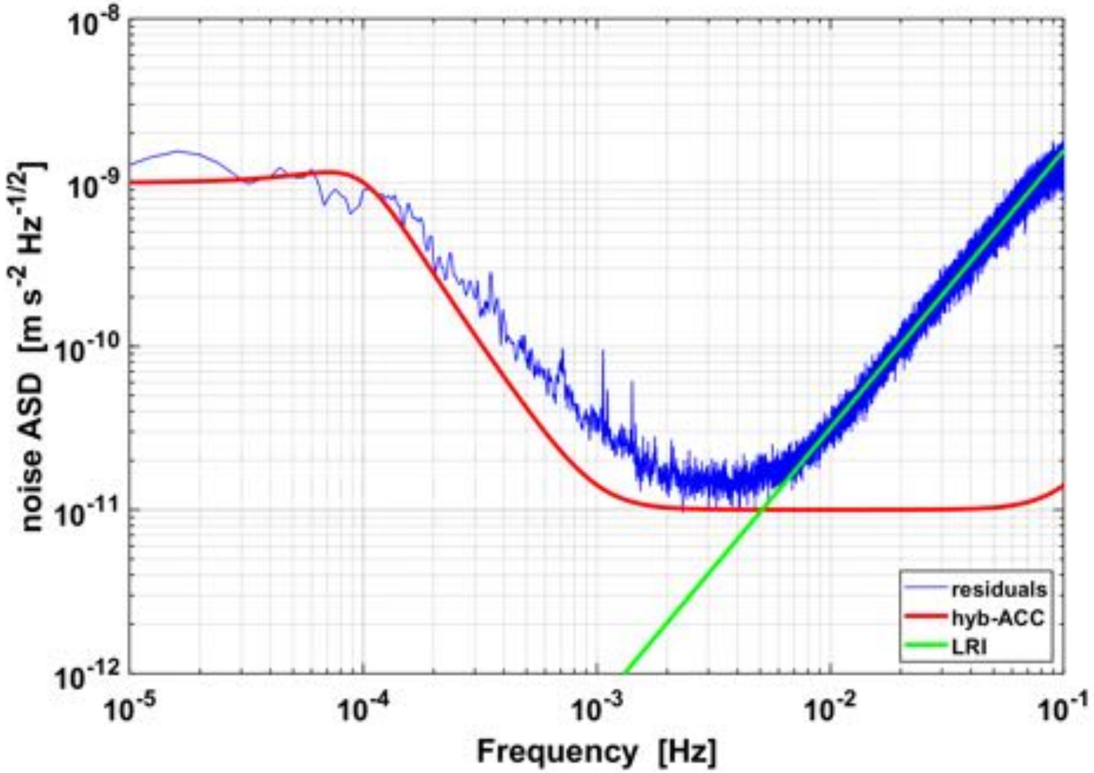



Scale limited to ±0.07m



# Scenario 3

| | Electrostatic ACC | CAI-ACC |
|---|---|---|
| 1 | $10^{-10}$ m s$^{-2}$ Hz$^{-1/2}$ | $10^{-9}$ m s$^{-2}$ Hz$^{-1/2}$ |
| 2 | $10^{-11}$ m s$^{-2}$ Hz$^{-1/2}$ | $10^{-9}$ m s$^{-2}$ Hz$^{-1/2}$ |
| **3** | **$10^{-12}$ m s$^{-2}$ Hz$^{-1/2}$** | **$10^{-11}$ m s$^{-2}$ Hz$^{-1/2}$** |

- Gravity Field Recovery for d/o 90
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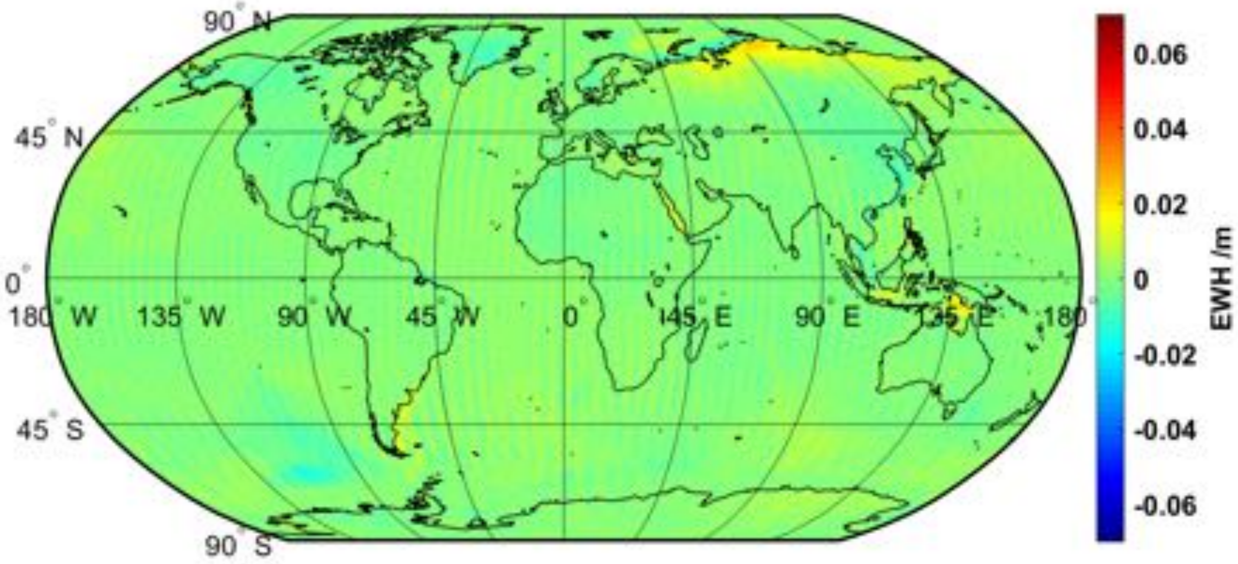


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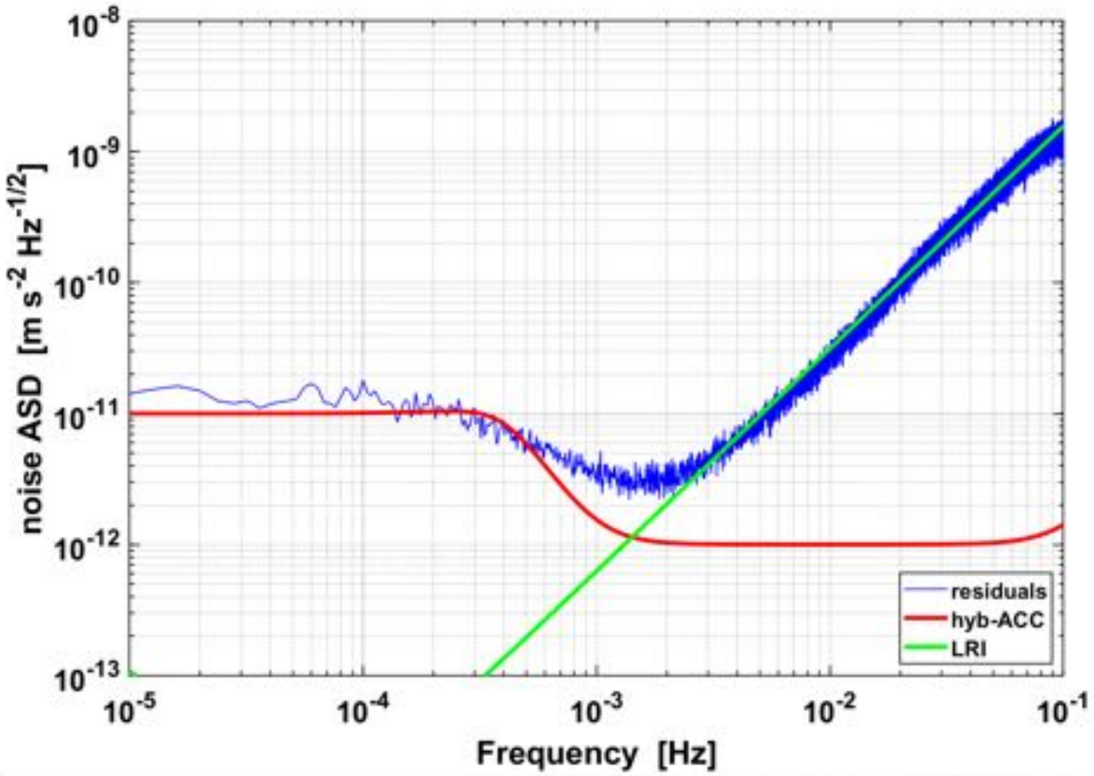
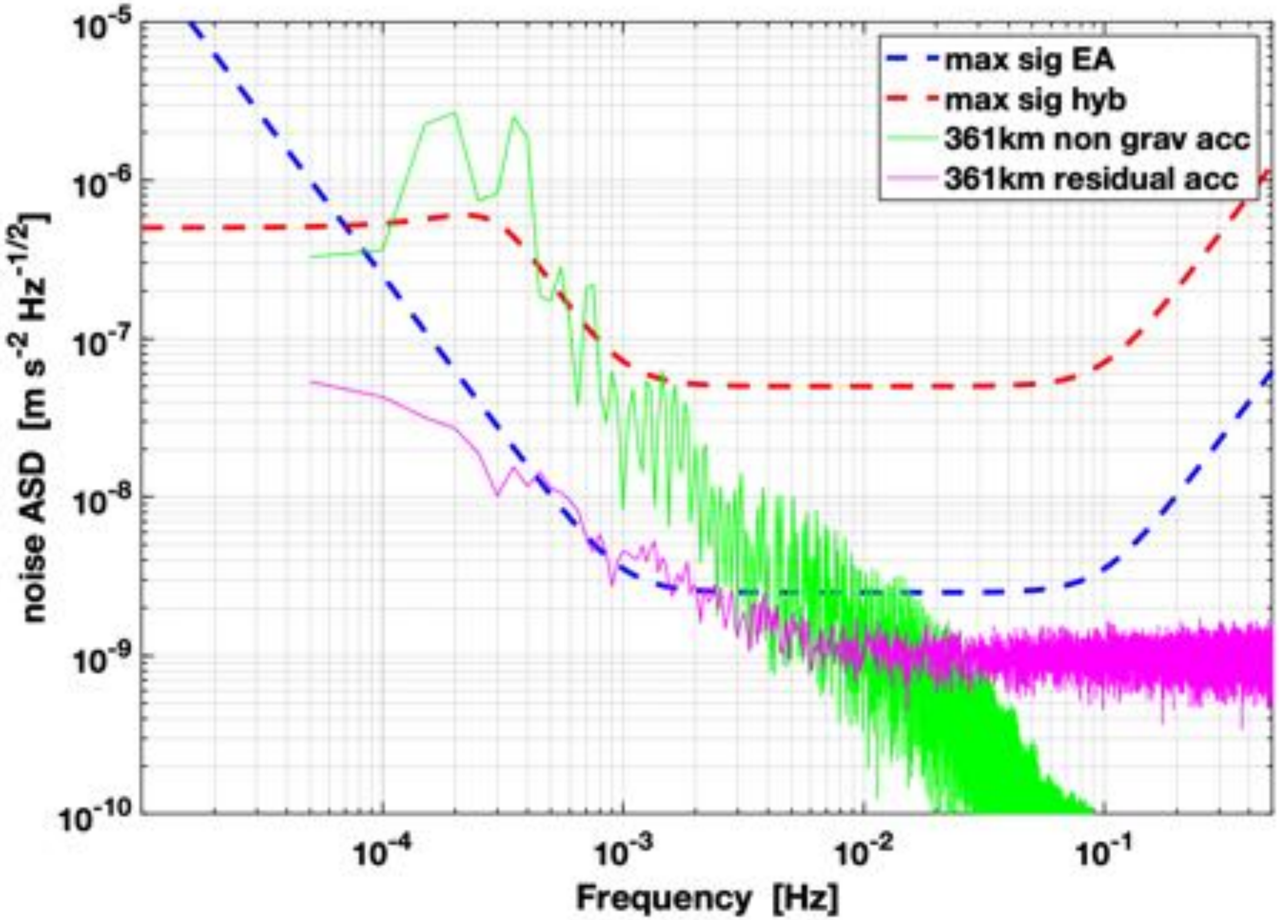


# ACC scale factor and drag compensation

Error due to scale factor depends on max acceleration signal (here only along track)

- Drag compensation (DC) to reduce accelerations within limit of ACC
- Requirement $R_{DC} = \frac{f(\text{ASD})}{2\sigma_{SF}}$ (c.f. Gruber2014)
- Scale factor knowledge $\sigma_{SF}$
    - EA: few per mile
    - Hybrid-ACC: calibration of EA with CAI → improvement 2 orders of magnitude, e.g. by laser frequency stabilisation

→ Less strict requirements for drag compensation in hybrid case




Along track non-gravitational acceleration and residual acceleration after DC with hybrid-ACC in 361km and maximum permissible signal after DC for GRACE type EA and hybrid-ACC.

# Conclusions

- Simulator for NGGM; currently based on GRACE-type concepts
- Improvements of accelerometers has a high priority and gain for GFR
- Cold Atom Interferometry brings major improvements in lower frequency range
- CAI enhances classical accelerometers, e.g. calibration

- CAI currently treated as "blackbox" in modelling
- Complementary CAI sensor development at DLR institute in the future

# Thank you for your attention

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