Novel sensor concepts for future gravity field satellite missions

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The present and future of Satellite Gravimetry
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German Aerospace Center (DLR)

2018 Foundation of institutes focusing on quantum technologies

- Galileo competence center (Oberpfaffenhofen)
- Quantum communication and cryptography (Ulm)
- Quantum sensing and metrology (Hannover)
    - Startup phase
    - Development of inertial sensors for space and terrestrial applications
    - Geodetic applications and reference systems

Institute for Satellite Geodesy and Inertial Sensing

This presentation

- Satellite Geodesy and Geodetic Modeling
- Quantum Sensing
- Quantum Optical Sensing
- Optical Frequency Metrology and Optical Reference Systems
- Relativistic Modeling

Outline

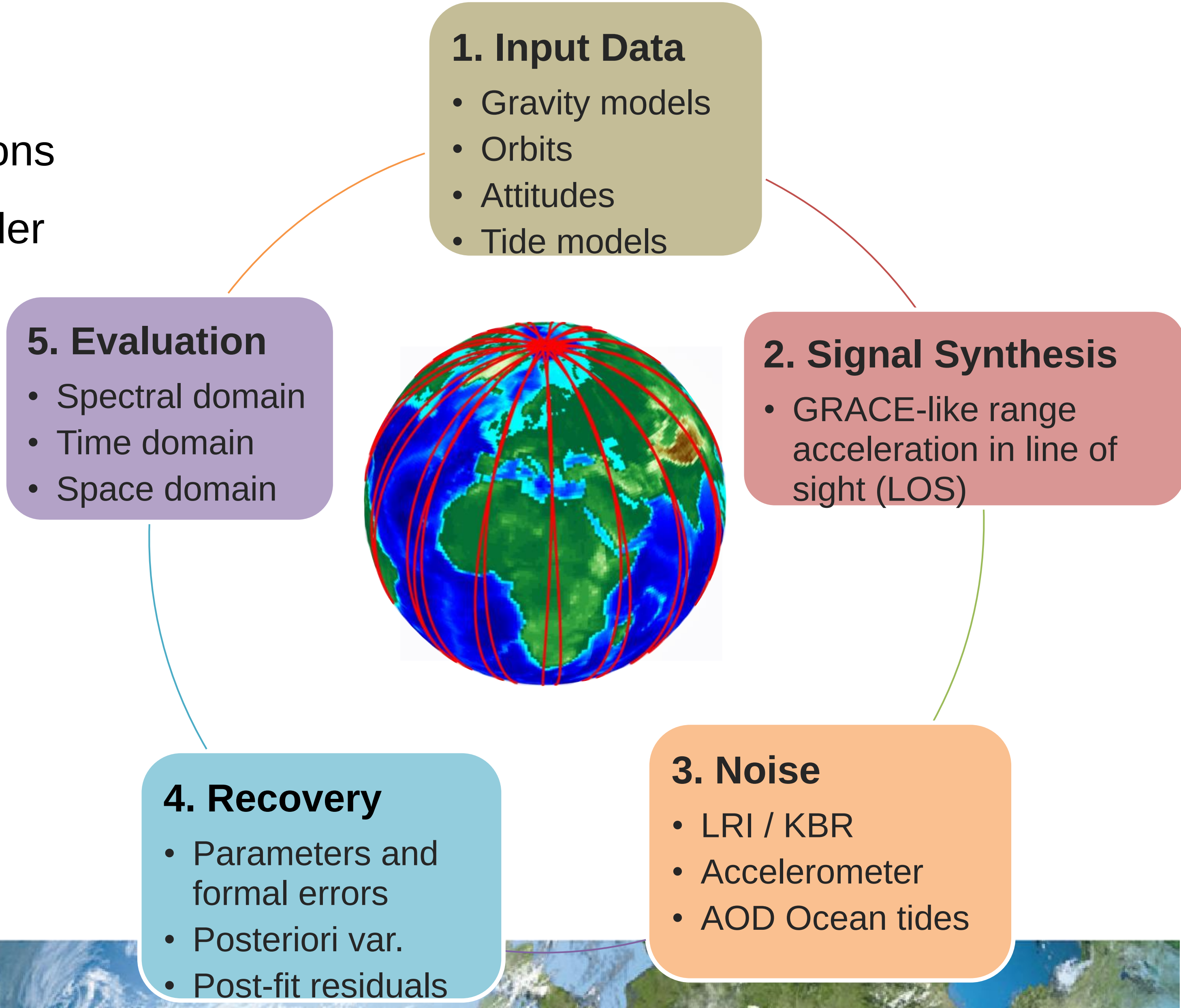
Overview of initial work in satellite geodesy

- Atom interferometry and accelerometers
- Optical clocks as support for satellite gravimetry
- Conclusions

Closed loop simulation

Studies are based on closed loop simulations

- Simulator for GRACE-type scenarios under development
- Based on GOCE GFR [Wu2016] and adapted for ranging observations
    - Error free observations + noise
- Investigate impact of e.g. instrumental noise, different orbit configurations
- Compare recovered gravity field to input gravity field



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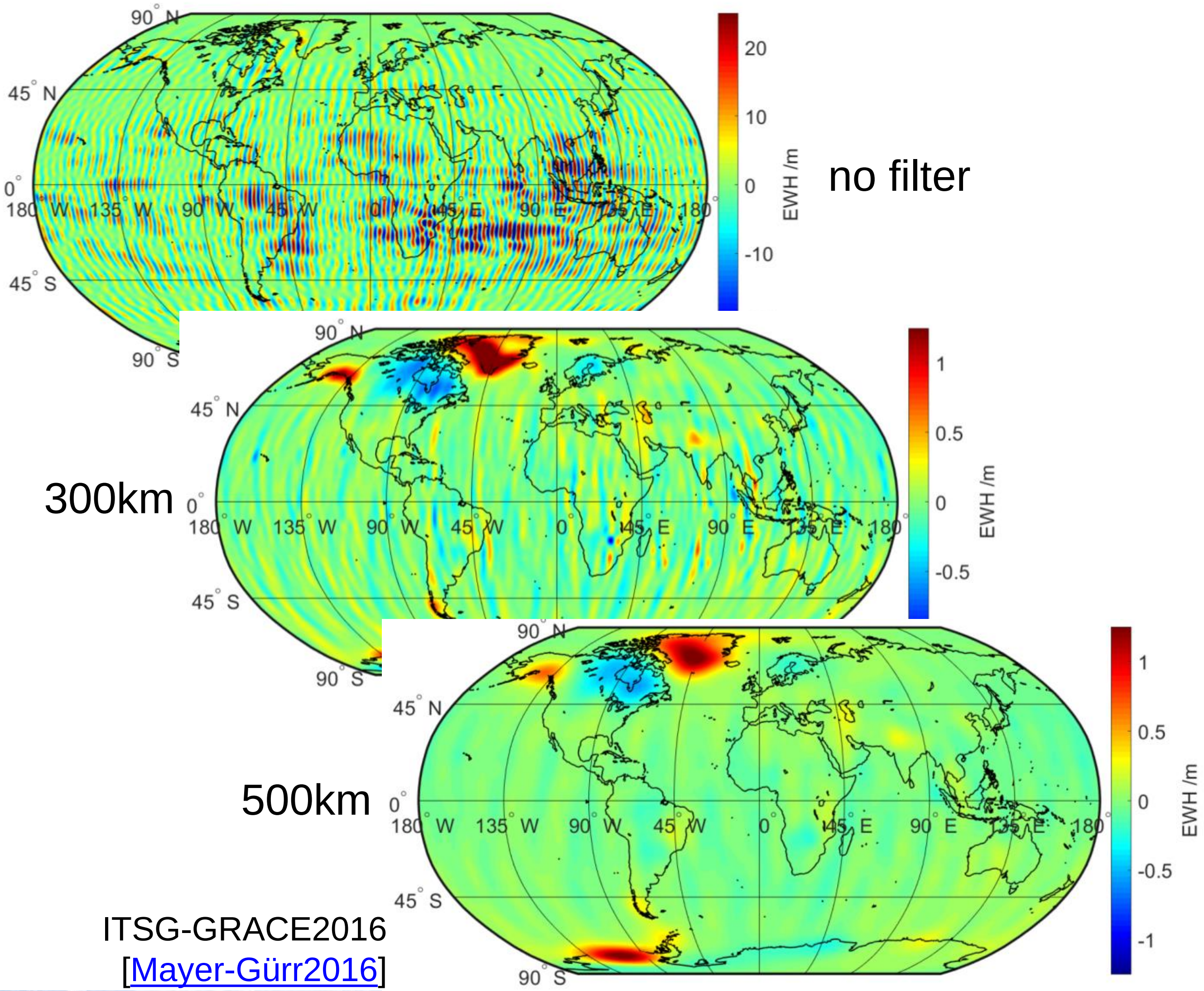
Current GRACE and GRACE-FO solutions

Striping effects

- Due to predominantly N-S observations
- Reduction by signal processing methods

Possible improvements → "less" processing

- Sensors, e.g. ACC
- Observations in E-W direction
  - Multiple pairs, e.g. "Bender"
  - New observation types, e.g. from advanced LRI



ITSG-GRACE2016 [Mayer-Gürr2016]

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Atom interferometry concept

Cold atoms as test masses in an interferometer

Leading order phase shift $\Delta\Phi$

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

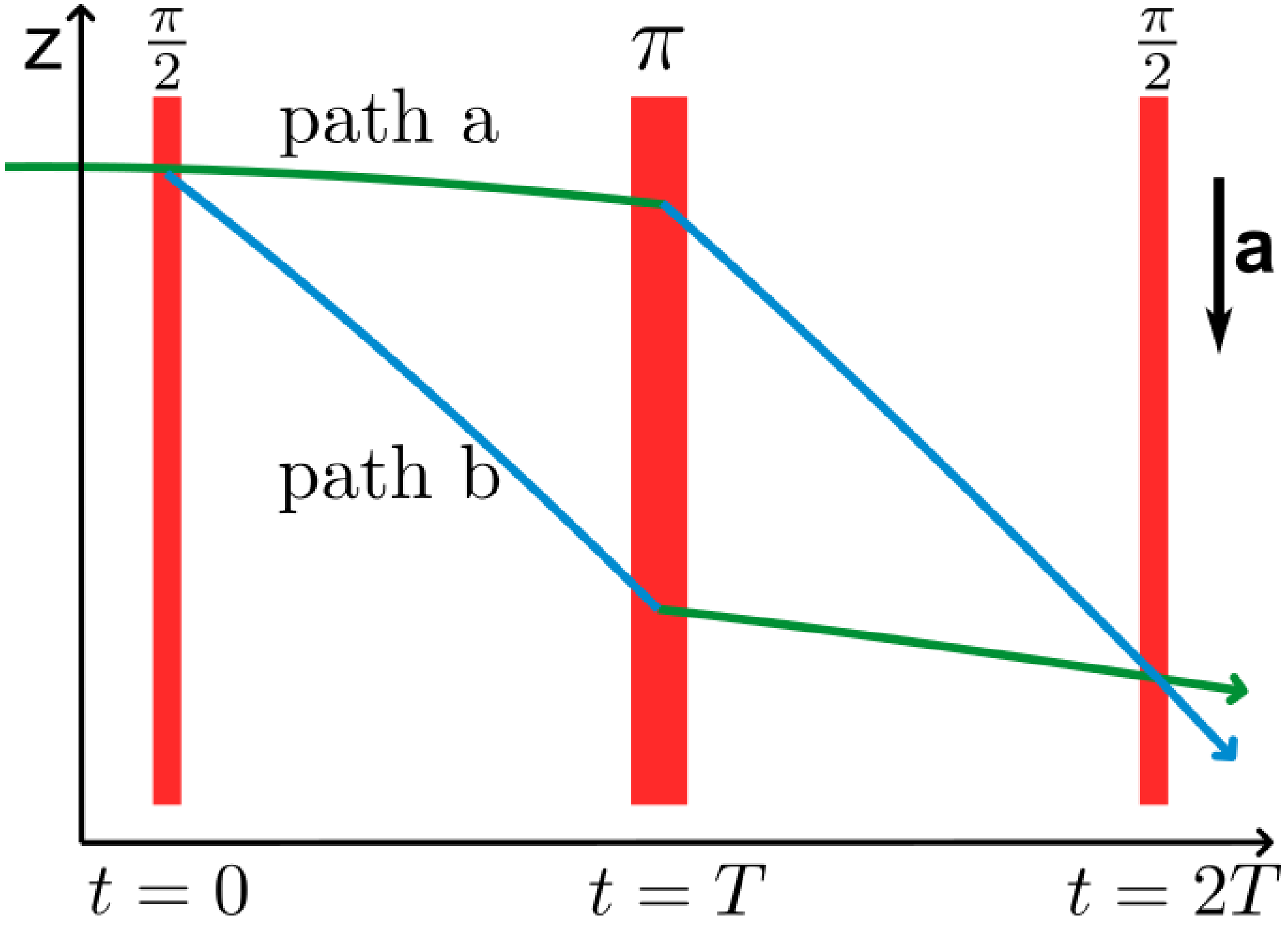
One axis, e.g. along track: $\mathbf{k}_{\mathrm{eff}} || \mathbf{a}$

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

Frequency chirp α (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

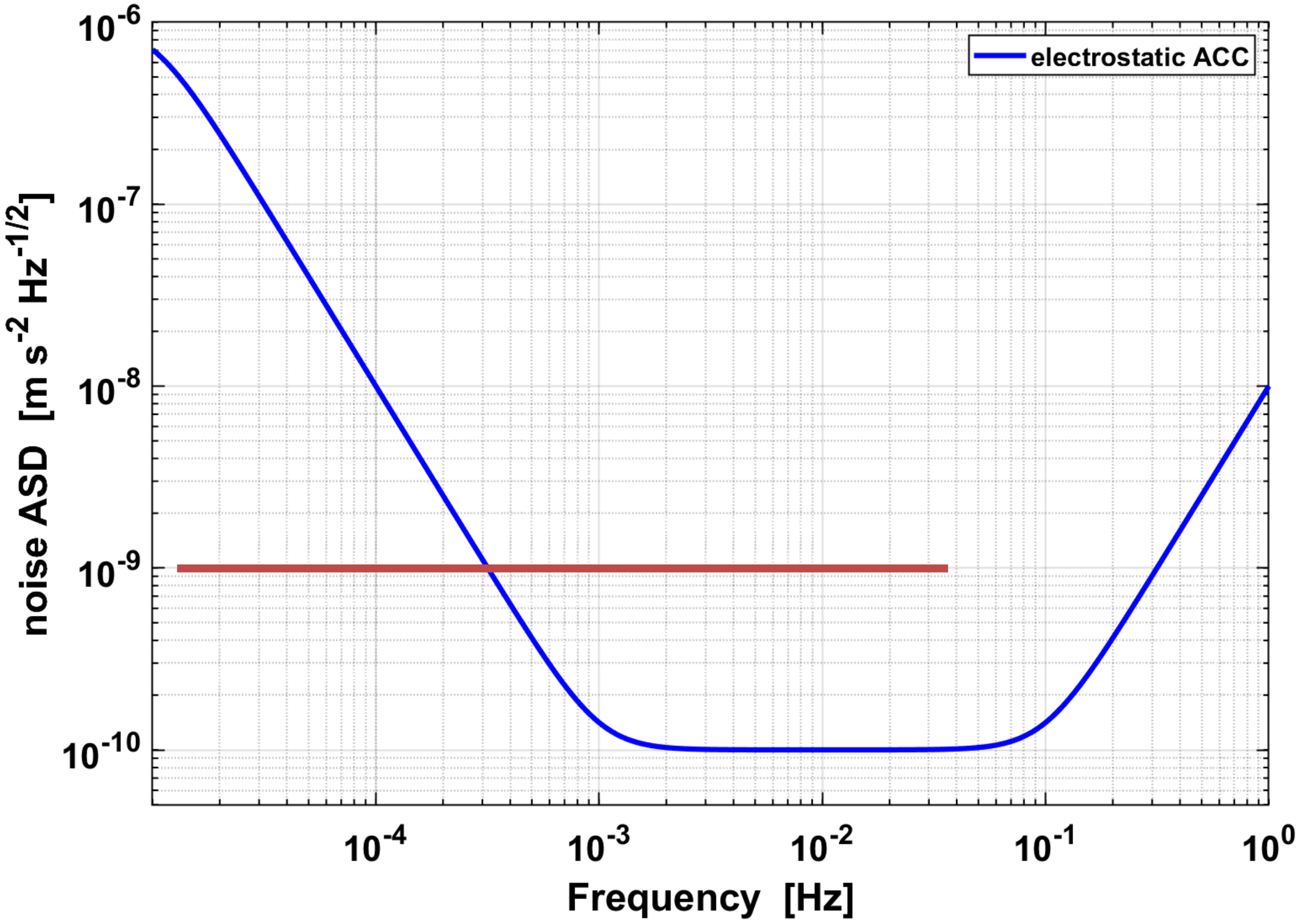
Improving the accelerometer with CAI

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]

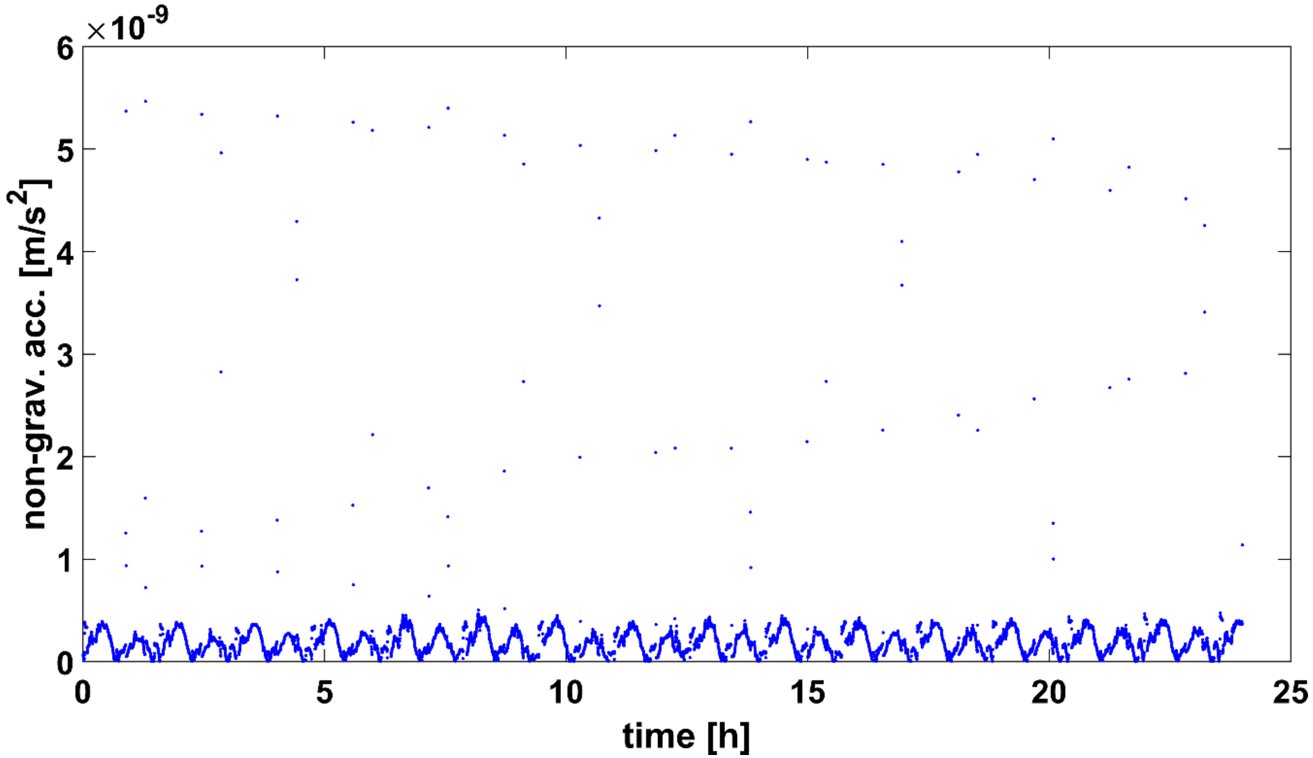
Improving the accelerometer with CAI

Combining a hybrid-ACC

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

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

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



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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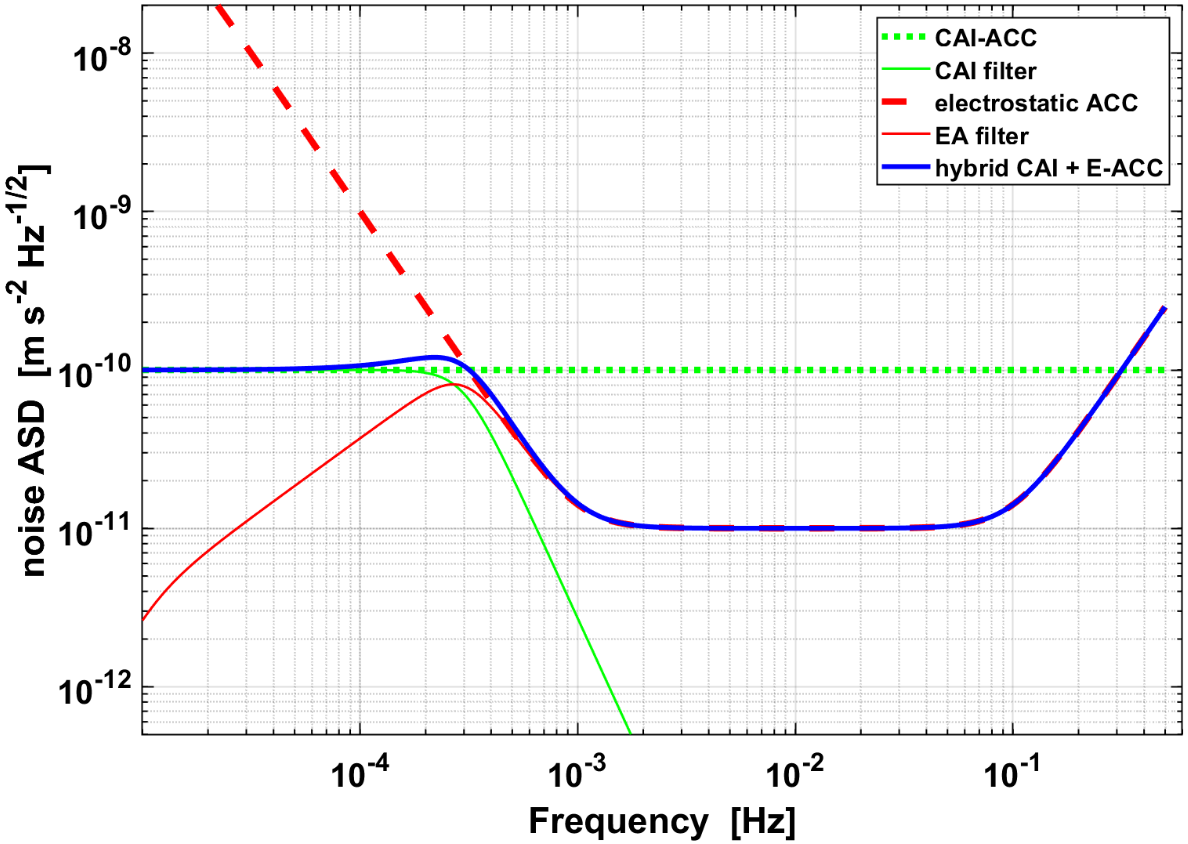
Filter strategy

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



Combination of electrostatic and CAI- ACC

Improving the accelerometer with CAI

Combining a hybrid-ACC

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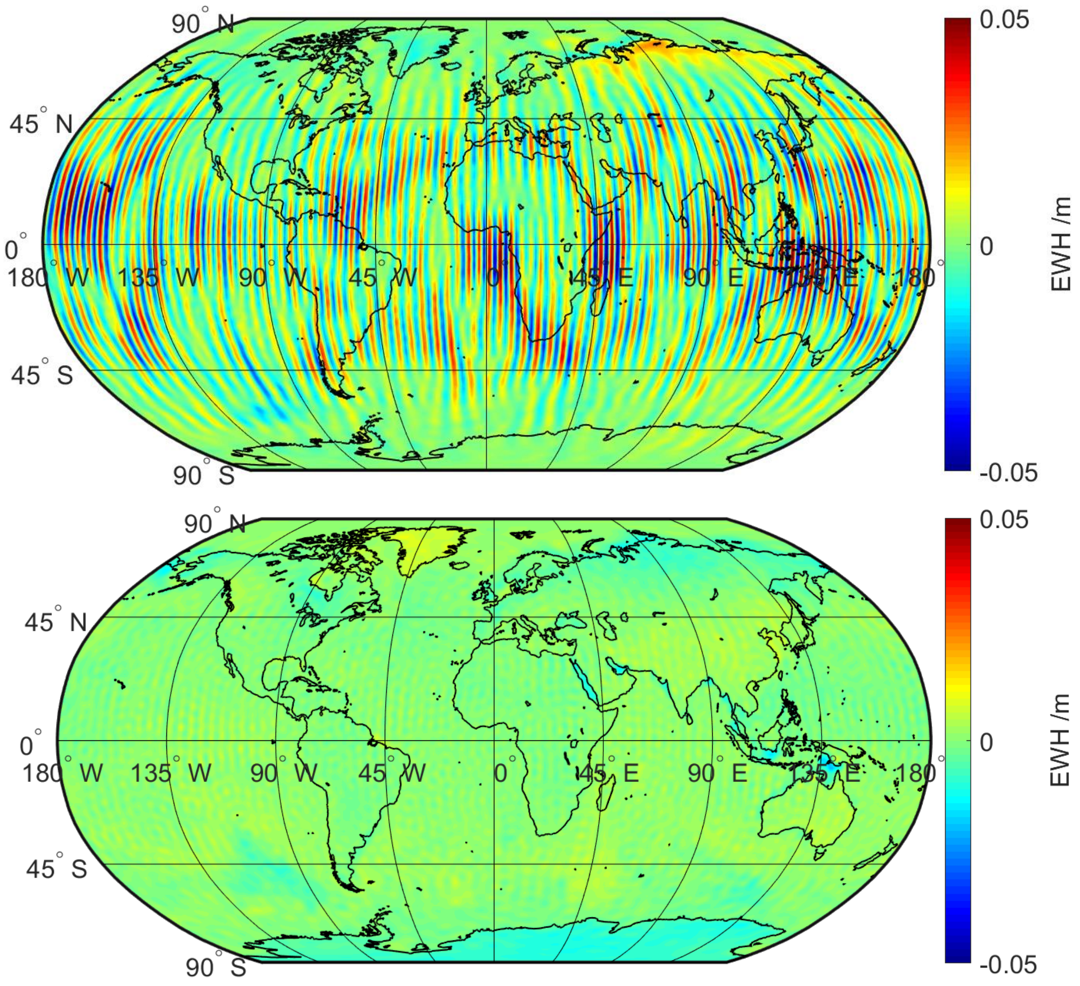


Difference of static input and recovered gravity field with different ACC types (colorbar limited to ±5cm)

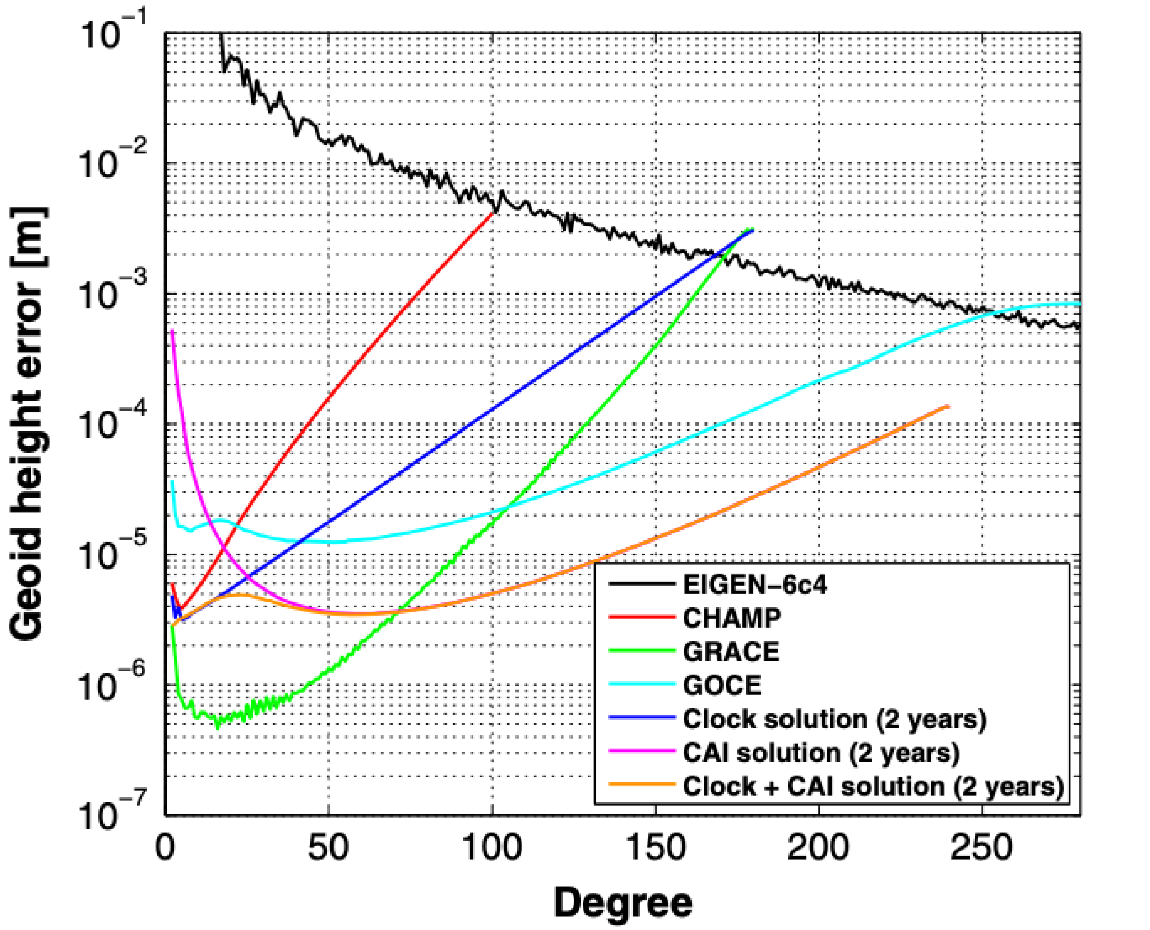
Optical clocks for gravity field determination

- Gravitational potential difference from frequency comparison

$$\frac{\Delta f}{f} = \frac{f_B - f_A}{f_A} = \frac{\Delta W}{c^2} + O(c^{-4})$$

- On ground: fiber-links at $\approx 10^{-19}$ uncertainty
- In space more challenging
  - Clock with $\approx 10^{-18}$ uncertainty for d/o<12

→ Currently beyond technological feasibility



Comparison of degree medians of the formal errors (geoid height) of CHAMP (AIUB-CHAMP03s), GRACE (ITG- Grace2010s),GOCE (EGM_TIM_RL5) and CAI + clock scaled to 2 years [Müller2020]

Conclusions

- Update of simulator for noise modelling and GFR for novel CAI sensors
- Atom interferometry based accelerometers have a high potential for improved GFR
- Optical clocks can (in the long term) provide gravity field information

Future activities

- Geodetic modelling related to new mission and sensor concepts
- Sensor development in other departments in parallel to geodetic simulation

Thank you for your attention

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Atominterferometry

Atom energy E change

$$\Delta E_{1,2} = h(f_1 - f_2)$$

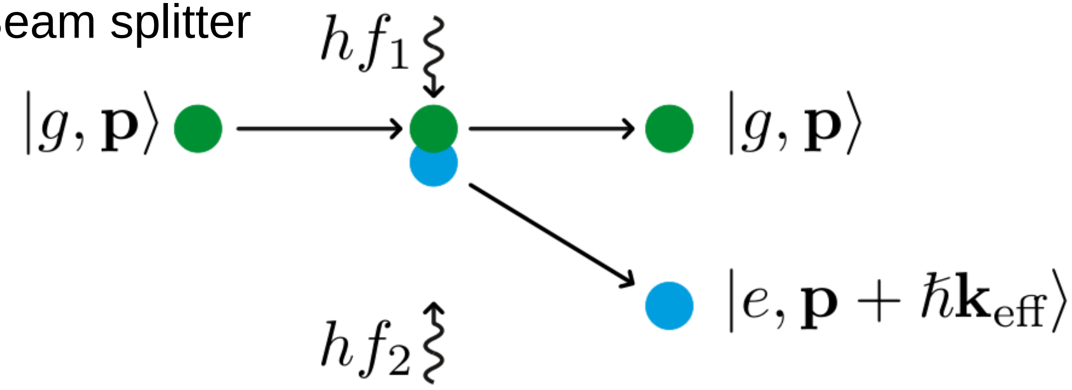
Atom momentum $\mathbf{p}$ change

$$\Delta \mathbf{p} = \hbar(\mathbf{k}_1 - \mathbf{k}_2) = \hbar \mathbf{k}_{\mathrm{eff}}$$

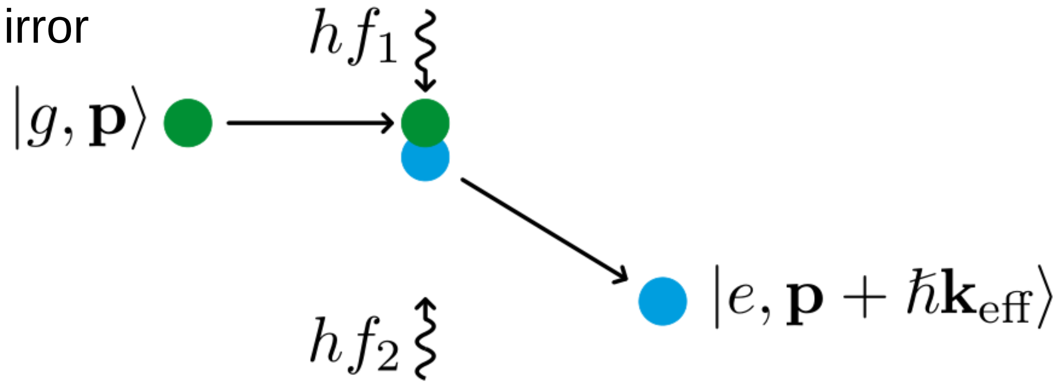
Quantum optical methods

- *Beam splitter* 50% probability
- *Mirror* 100% probability

Beam splitter



Mirror



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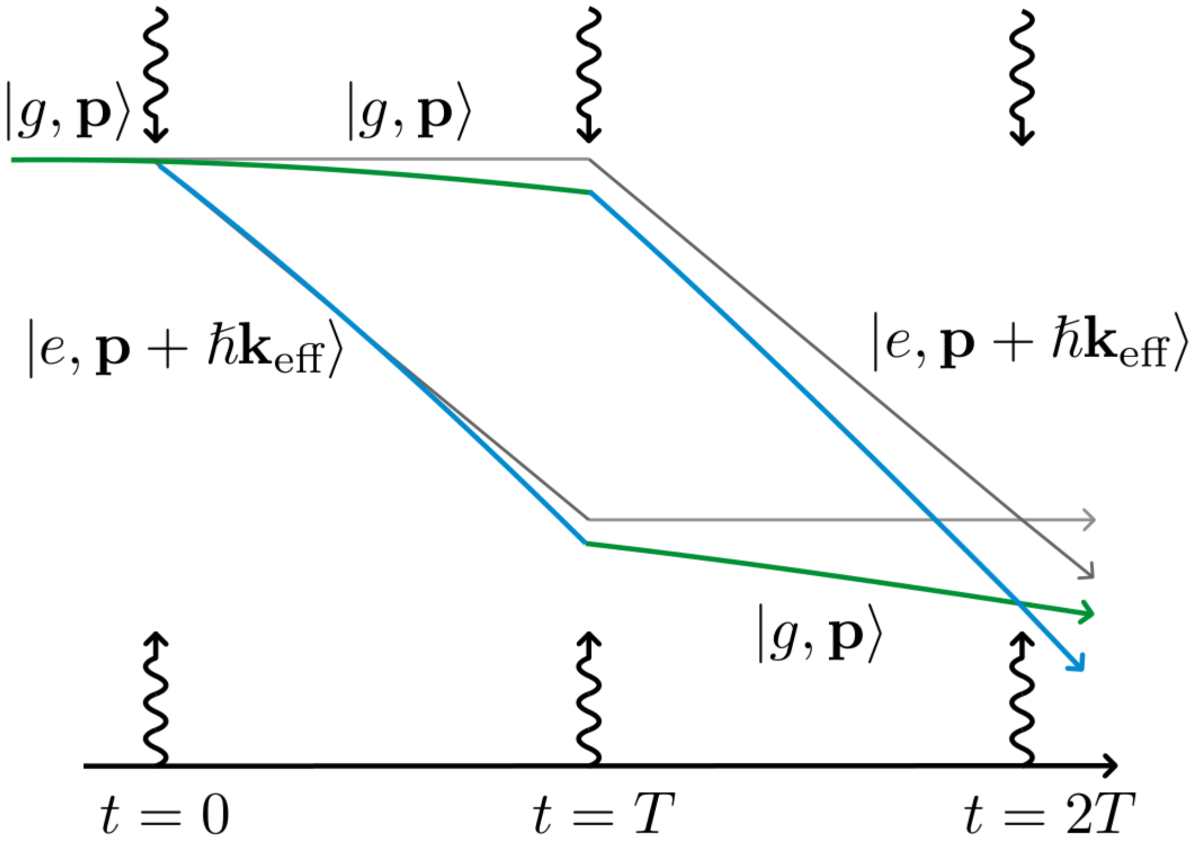
Atominterferometry

Measurement of population $P_{|e\rangle}$ after $2T$

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

Interferometer phase shift

$$\Delta\Phi = (\mathbf{k}_{\text{eff}}\mathbf{a} - \alpha)T^2 - \phi_l$$



Mach-Zehnder Interferometer

Kasevich, M. A., & Chu, S. (1991). Atomic interferometry using stimulated Raman transitions. *Phys. Rev. Lett. 67*(2), 181–184