Novel sensor concepts for future gravity field satellite missions

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The present and future of Satellite Gravimetry
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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

This presentation
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
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
Atom interferometry concept

Cold atoms as test masses in an interferometer

Leading order phase shift $\Delta \Phi$

\[ \Delta \Phi = k_{\text{eff}} \cdot a \cdot T^2 \]

One axis, e.g. along track: $k_{\text{eff}} \parallel a$

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

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 ($< 10^{-3}$ Hz) drift → limit low d/o coefficients

Adding CAI to form a hybrid-ACC
- White noise $10^{-9} \text{ms}^{-2}/\sqrt{\text{Hz}}$
  e.g. performance of GAIN [Freier2017]
- Improvement in lower frequencies
- Is white noise a realistic assumption?
Improving the accelerometer with CAI

Combining a hybrid-ACC
• Data rate EA $>> 1$Hz
• CAI sensitivity increases with time
  \[ \Delta \Phi = k_{\text{eff}} \cdot a T^2 \]
• CAI measurement of several seconds  
  $\Rightarrow$ 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
- Data rate EA $>> 1$Hz
- CAI sensitivity increases with time
  \[ \Delta \Phi = k_{\text{eff}} \cdot a T^2 \]
- CAI measurement of several seconds $\to$ Change of non grav. force $a$ during $T$

Filter strategy
- Low-/Highpass filter
- Kalman filter
- Suitable for drag-free control?
Improving the accelerometer with CAI

Combining a hybrid-ACC
- Data rate EA $>>$ 1Hz
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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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References

Atominterferometry

Atom energy $E$ change

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

Atom momentum $p$ change

$$\Delta p = \hbar (k_1 - k_2) = \hbar k_{\text{eff}}$$

Quantum optical methods

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

Atominterferometry

Measurement of population $P|e\rangle$ after $2T$

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

Interferometer phase shift

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