Using Quantum Sensors On-board Satellites for Determining the Earth's Gravity Field

Jürgen Müller and Hu Wu

Institut für Erdmessung (IfE), Leibniz Universität Hannover, Germany

Motivation

In the past decades, satellite missions like GRACE and GOCE have advanced our knowledge on the Earth's gravity field, by measuring the first- and second-order derivatives of the gravitational potential. However, a more precise gravity field model with a better spatio-temporal resolution is still highly demanded for geodetic and further geoscience applications. In recent years, new technologies based on quantum optics emerged and quickly developed, which will enable novel observation concepts and deliver gravimetric observations with an unprecedented accuracy in future. For the first time, atomic clocks provide a particular opportunity to directly observe gravity potential differences through measuring the relativistic redshift between clocks ("relativistic geodesy"). A quantum gradiometer, e.g., the Cold Atom Interferometry (CAI) gradiometer, is expected to deliver gravity gradients with an accuracy of about one order of magnitude higher than that of GOCE. In this study, the benefit of such new sensors on determining the Earth's gravity field is evaluated, where the instrumental errors are mapped to the gravity field coefficients through closed-loop simulations.

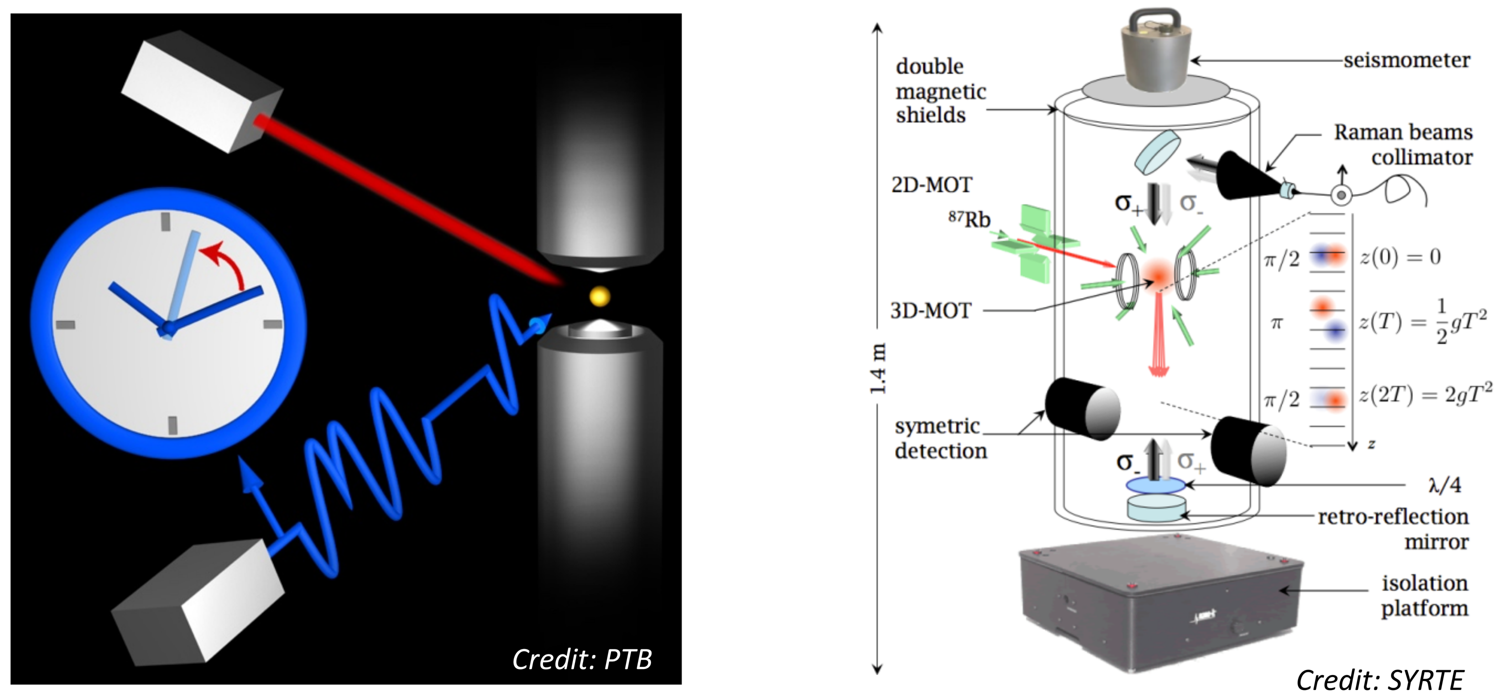

Fig. 1: Scheme of a single-ion optical clock (left) and the Cold Atom Interferometry (CAI) gravimeter (right).

Retrieving the Earth's gravity field

The global gravitational field is expressed as

$$V = \frac{GM}{R}\sum_{n=0}^{\infty}\left(\frac{R}{r}\right)^{n+1}\sum_{m=-n}^{n}\bar{K}_{nm}\,\bar{Y}_{nm}(\theta,\lambda),$$

$$\bar{Y}_{nm}(\theta,\lambda) = \bar{P}_{nm}(cos\theta)e^{im\lambda}.$$

It can be retrieved by observing

- potential values (V)
- gravitational accelerations ($V_i = \frac{\partial V}{\partial r_i}$)
- gravitational gradients ($V_{ij} = \frac{\partial^2 V}{\partial r_i \partial r_j}$)

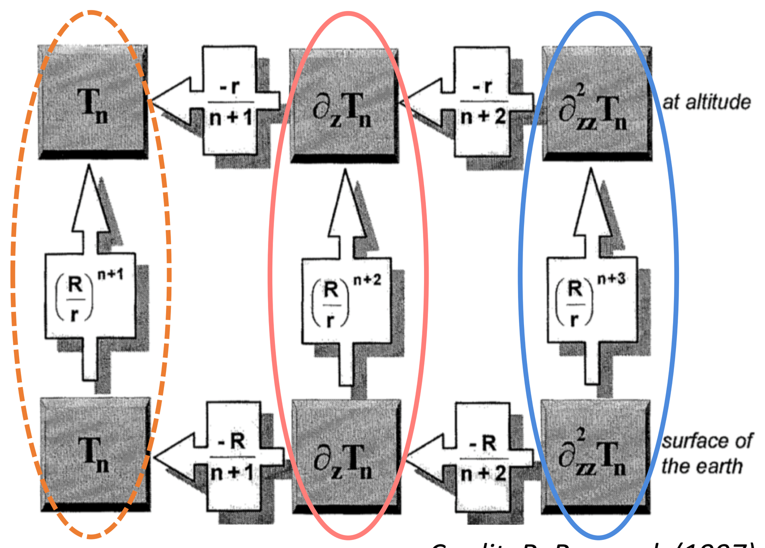

Fig. 2: Extended Meissl scheme. Detecting the Earth gravitational field by observing the zero-, first- and second-order derivatives of the gravitational potential in space. Note: $T = V - U$.

Closed-loop simulator

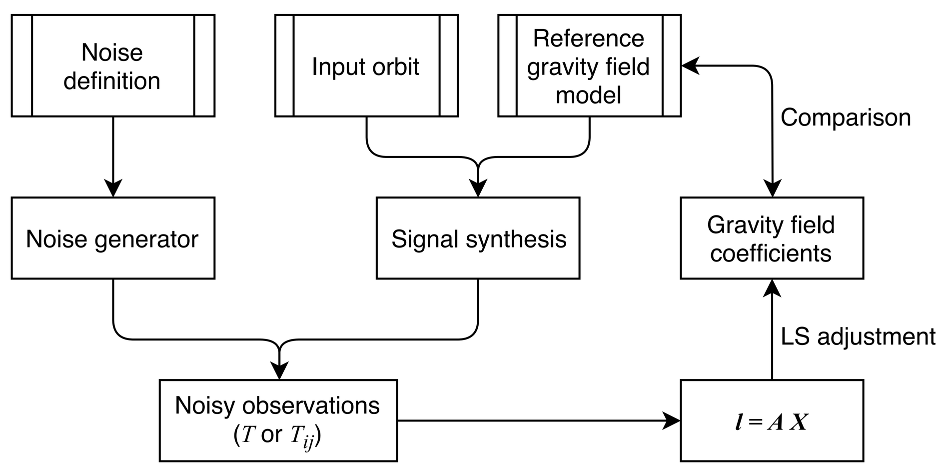

Fig. 3: Scheme of our closed-loop simulator for gravity field recovery from clock and CAI data. The observation signals are synthesized from a background model, here EIGEN-6C4. The noise is generated based on the specifications of the sensor behavior. A rigorous Least-Squares (LS) adjustment is applied to retrieve the gravity field coefficients, which are compared to the input model for evaluation.

Atomic clocks

- Basis: Einstein's general theory of relativity
- Gravitational redshift: $\frac{\Delta f_{21}}{f_1} = \frac{f_2 - f_1}{f_1} = \frac{V_2 - V_1}{c^2} + O\,(c^{-4})$
- Error propagation: $\frac{\Delta f}{f}\ (1.0 \times 10^{-18}) \sim \Delta V\ (0.1\ \mathrm{m^2/s^2}) \sim \Delta h\ (1.0\ \mathrm{cm})$

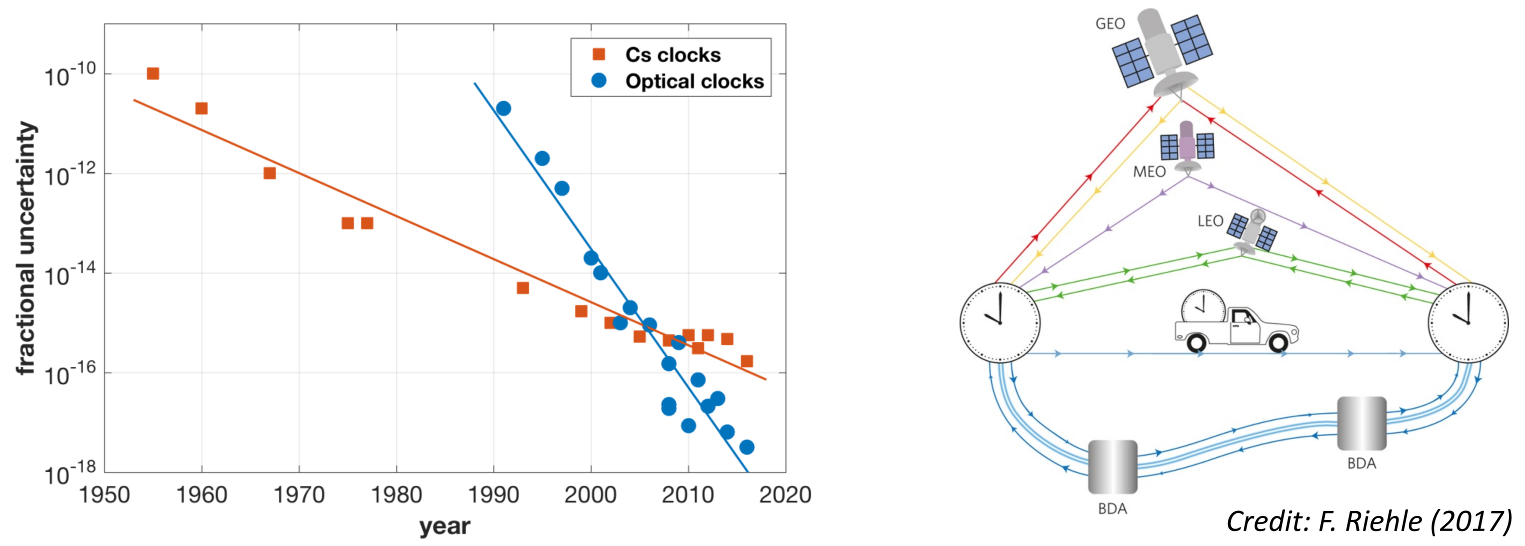

Fig. 4: Evolution of atomic clocks' performance (left) and various frequency link techniques (right). The frequency comparison between distant clocks is now approaching the level of 1.0×10^{-18}, which can be translated to a potential differences of about 0.1 m²/s².

Input for simulation

- Orbit: GOCE, two months (November and December, 2009), 5 s
- Model: EIGEN-6c4, d/o 360
- Clock error: white noise

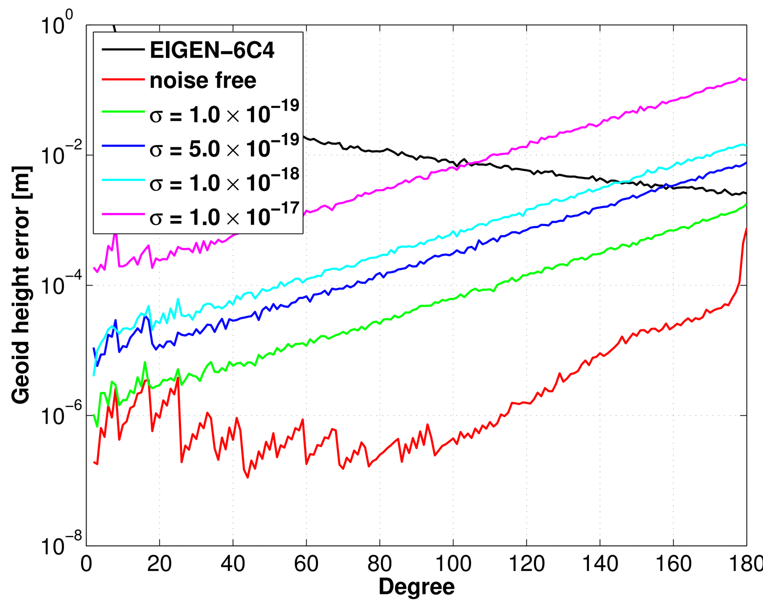

Fig. 5: Degree variances of gravity field coefficient differences w.r.t. EIGEN-6c4, in terms of geoid height. The models were recovered up to d/o 180. The zonal and near-zonal coefficients that are degraded by the polar gaps of the GOCE orbit have been excluded when computing the degree variances.

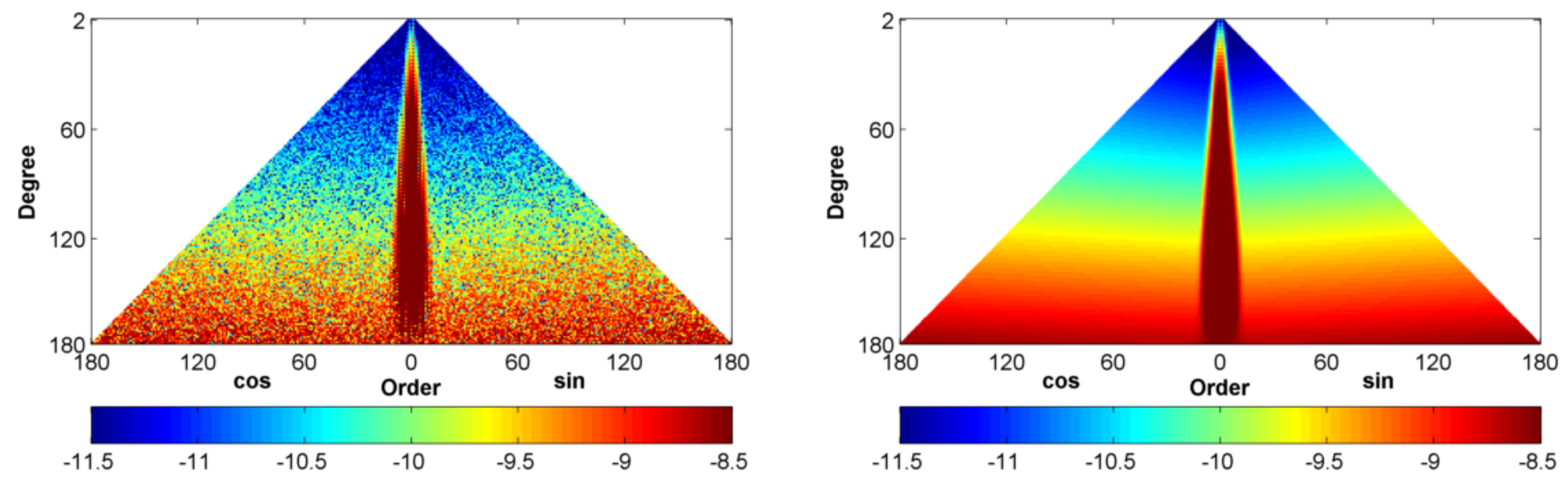

Fig. 6: Gravity field solution from clock data with a noise level of 1.0×10^{-18}. Coefficient differences w.r.t. EIGEN-6c4 (left) and the formal errors (right), in logarithm scale.

Potential for retrieving the time-variable gravity field

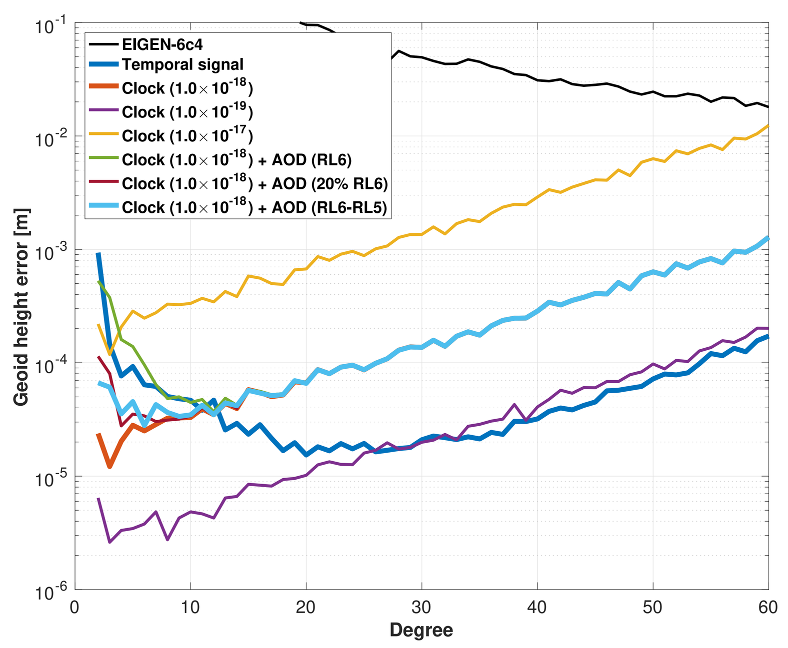

Fig. 7: Degree variances of coefficient differences (recovered models w.r.t. EIGEN-6c4). Different cases were compared.

Input for simulation

- Orbit: GRACE satellite A, one month (January 2006), 5 s
- Static model: EIGEN-6c4, d/o 180
- Time-variable model: GRACE GFZ RL6 unfiltered solution (January, 2006), d/o 60
- AOD error: difference between AOD RL6 and RL5, d/o 100
- Clock error: white noise

Cold Atom Interferometry (CAI) gradiometer

Compared to the electrostatic one, the CAI gradiometer has

- better sensitivity: $1.0 - 5.0\ \mathrm{mE}/\sqrt{\mathrm{Hz}}$;
- wide spectral range: flat noise down to very low frequencies.

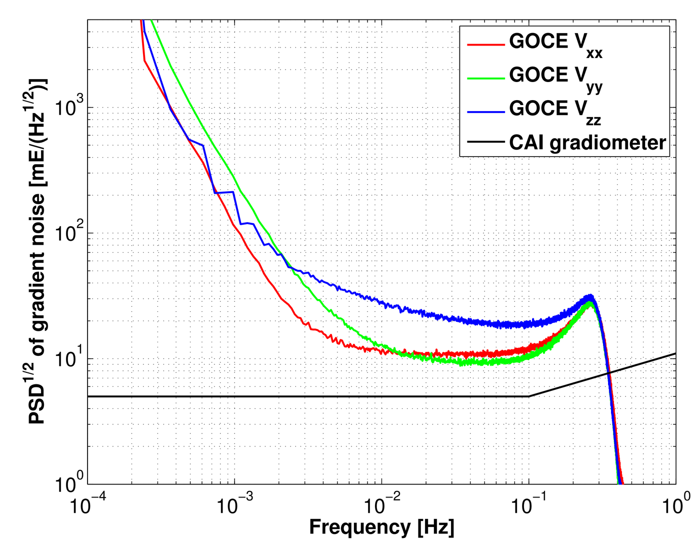

Fig. 8: Spectral noise behavior of the CAI gradiometer, compared to the GOCE gravity gradients.

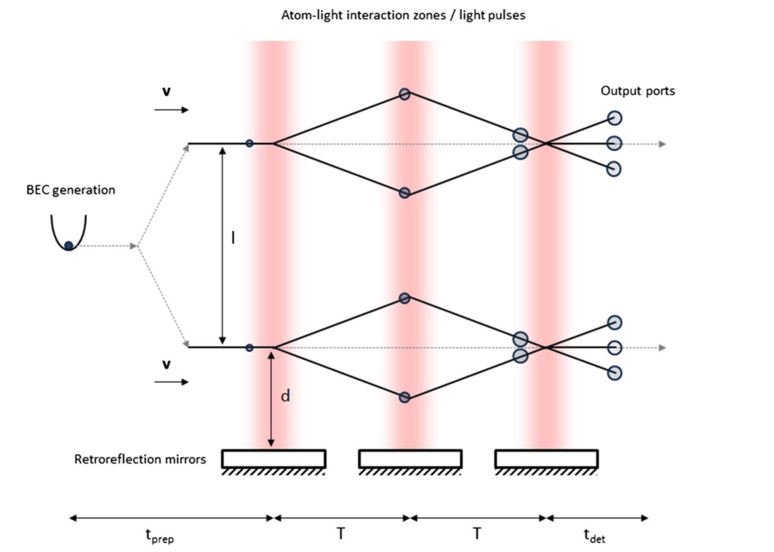

Fig. 9: Atom interferometry scheme for gradiometric measurements as proposed in Carraz et al. (2014).

Input for simulation

- Orbit: GOCE, 71 days (1st March – 10th May, 2013), 2 s
- Model: EIGEN-6c4, d/o 360
- Noise: white, $5.0\ \mathrm{mE}/\sqrt{\mathrm{Hz}}$

Two pointing modes

- Nadir:
  - one axis: V_{yy}
  - three axes (tilting mirror): V_{xx}, V_{yy}, V_{zz}
- Inertial: V_{xx}, V_{yy}, V_{zz}

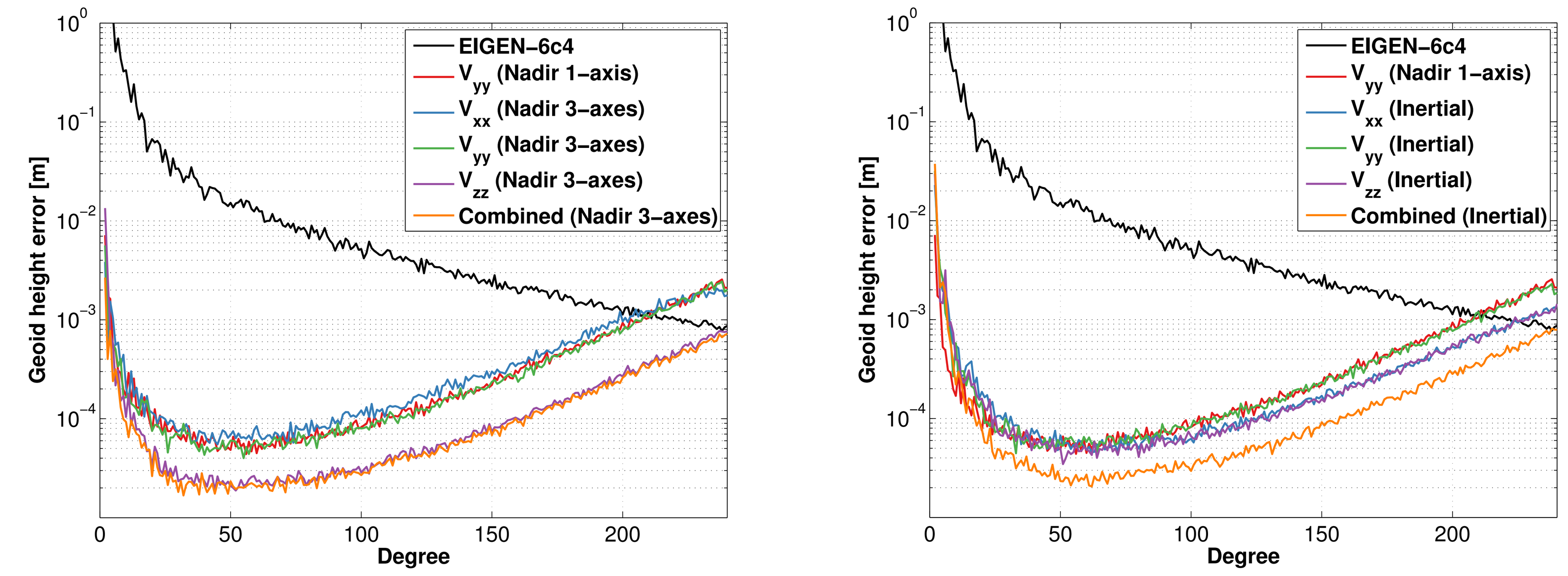

Fig. 10: Degree medians of gravity field coefficient differences w.r.t. EIGEN-6c4, in terms of geoid height. The left figure shows results in the nadir mode while the right one shows results in the inertial mode. All CAI models were recovered up to d/o 240. For more details about pointing modes, we refer to Douch et al. (2018).

Combined analysis

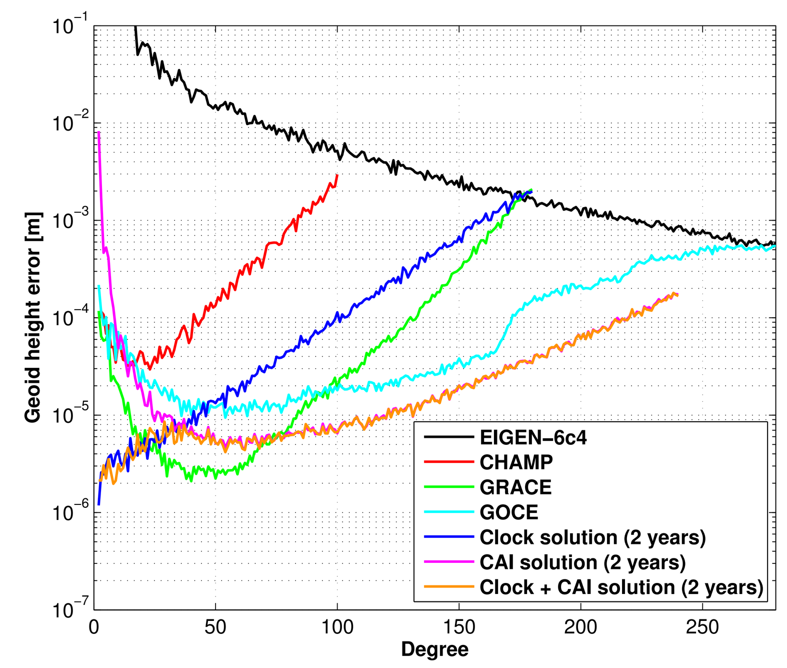

Fig. 11: Degree medians of gravity field coefficient differences w.r.t. EIGEN-6c4, in terms of geoid height. To compare with the official CHAMP, GRACE and GOCE gravity field solutions, we scaled the clock, CAI and their combined solutions to two years.

Conclusions

- Clocks can deliver the gravity potential, which is a scalar quantity and will be more robust to attitude errors;
- Clocks at the level of 10^{-18} can improve the long-wavelength gravity field, and could detect time-variable gravity field signals below d/o 15;
- CAI gradiometry in 3-axes modes outperforms GOCE by more than a factor of 5.

Acknowledgements

This work is supported by the DFG Collaborative Research Center 1128 "Relativistic Geodesy and Gravimetry with Quantum Sensors (geo-Q)". This work was also partly supported by the ESA project "Study of a CAI gradiometer sensor and mission concepts" and the ISSI team of research on "Spacetime metrology, clocks and relativistic geodesy".

Poster ID: EGU2019-6799

Vienna, Austria | April 7-12, 2019

Contact: {mueller, wuhu}@ife.uni-hannover.de
www.ife.uni-hannover.de