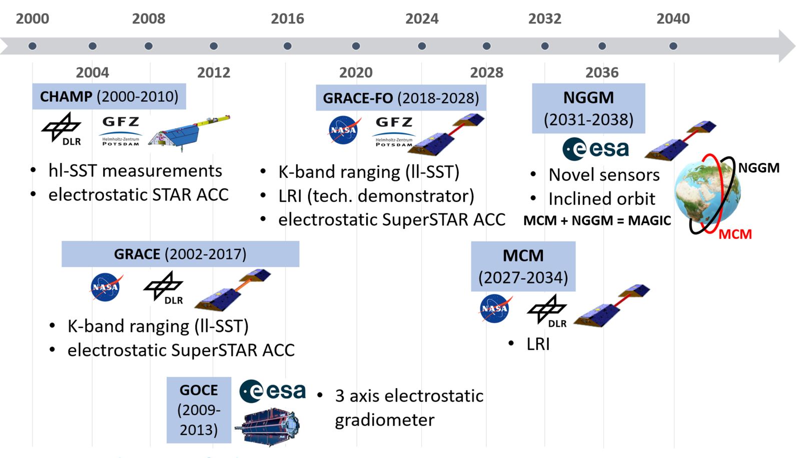
Beyond MAGIC: Evaluation of Novel Sensors and Satellite Formation Flights for Future Gravimetry Missions

Alexey Kupriyanov (1), Arthur Reis (2,3), Manuel Schilling (4), Annike Knabe (1), Nina Fletling (1), Alireza HosseiniArani (1), Mohsen Romeshkani (1), Vitali Müller (2,3), Jürgen Müller (1)

(1) – Institute of Geodesy, Leibniz University Hannover, Germany; (2) – Max Planck Institute for Gravitational Physics, Albert Einstein Institute, Hannover, Germany; (3) – Institute for Gravitational Physics, Leibniz University Hannover, Germany; (4) – Institute for Satellite Geodesy and Inertial Sensing, German Aerospace Center (DLR), Hannover, Germany

1. Motivation

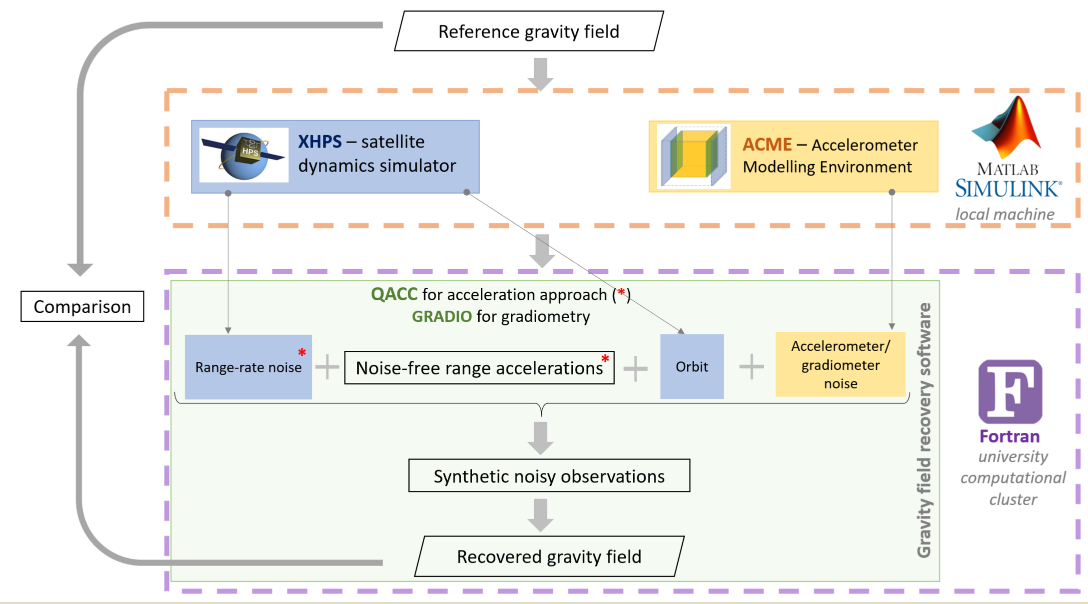
- >20 years satellite gravimetry missions provided unique data about mass redistribution processes in the Earth system
- Ongoing climate change underlines the urgent need to continue gravimetry measurements with enhanced concepts and sensors
- Low-frequency noise of electrostatic accelerometers (EA) - one of the limiting factors in gravity field recovery (GFR)



Timeline of the gravimetry missions
[modified based on the talk by H.Dobslaw in 'Satellitengeodäsie und geodätische Modellierung' on 18.01.2023, Hannover]

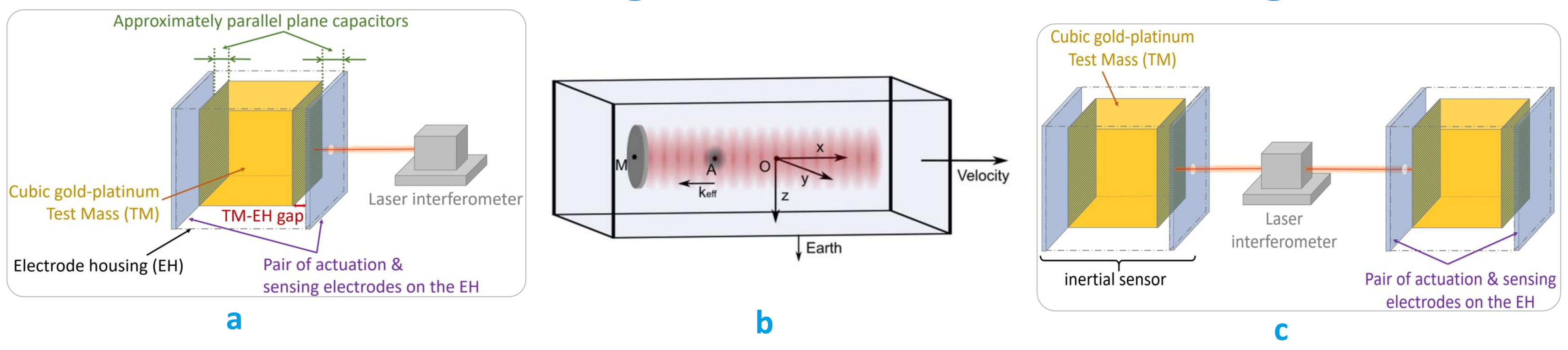
2. Simulation procedure

- Satellite dynamics were run in eXtended Hybrid simulation Platform for Space systems (**XHPS**) in Matlab/Simulink, including simulation of space environment
- Accelerometer Modeling Environment (**ACME**) is a framework developed in Matlab/Simulink to model past, current and proposed quantum accelerometers (ACCs)
- Gravity field recovery (GFR) was carried out using Quantum Accelerometry (**QACC**) [for acceleration approach] and **GRADIO** [for gradiometry] software tools, written in Fortran
- **Project goal** is to analyse instrument limits: only static gravity field, no temporal aliasing errors



Block diagram of the simulation procedure within the used software parts

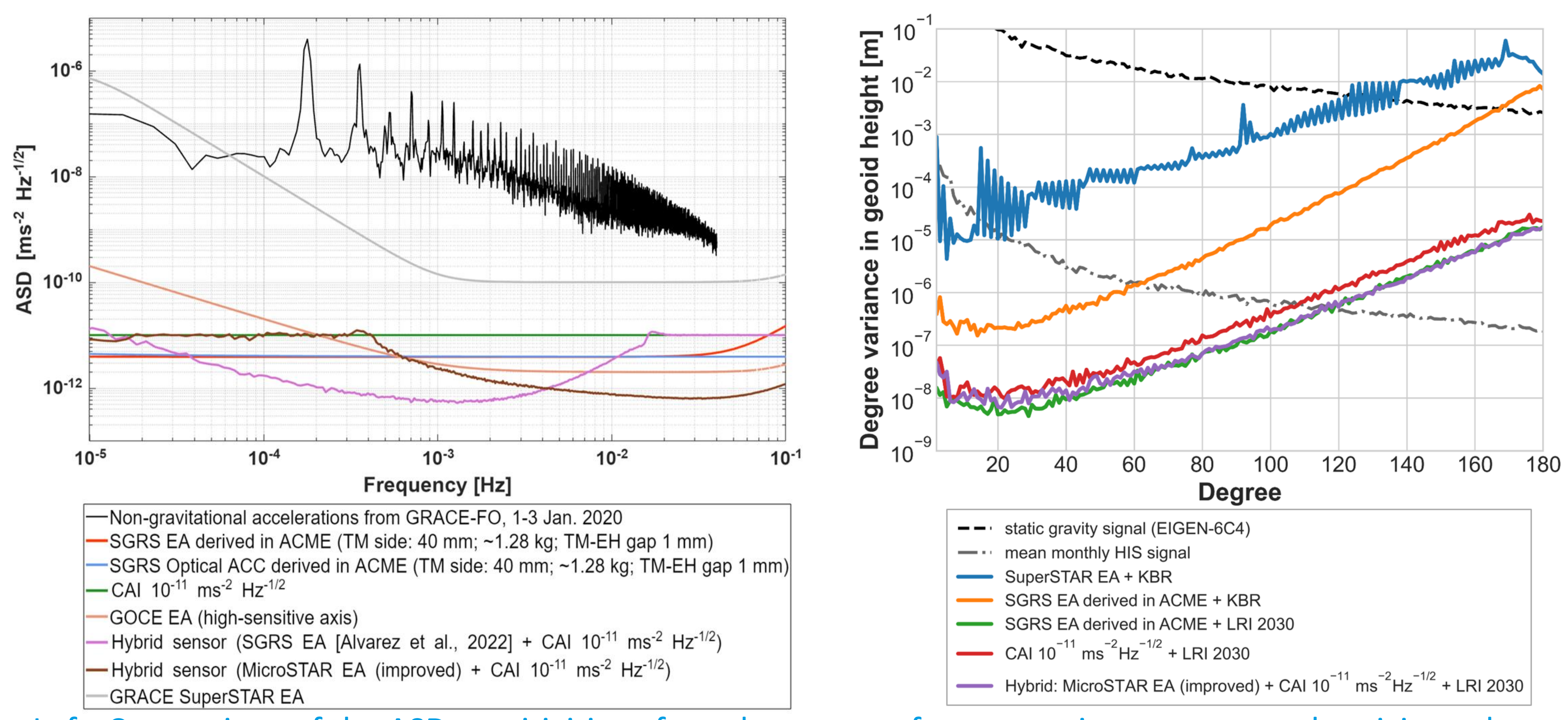
3. Accelerometers & gradiometers modeling



a: Illustration of 1 degree of freedom optical accelerometer model;
b: Cold atom interferometry (CAI) accelerometer geometry [Beaufils et al., 2023];
c: Scheme of the 1 degree of freedom optical gradiometer

4. Gravity field recovery | ll-sst

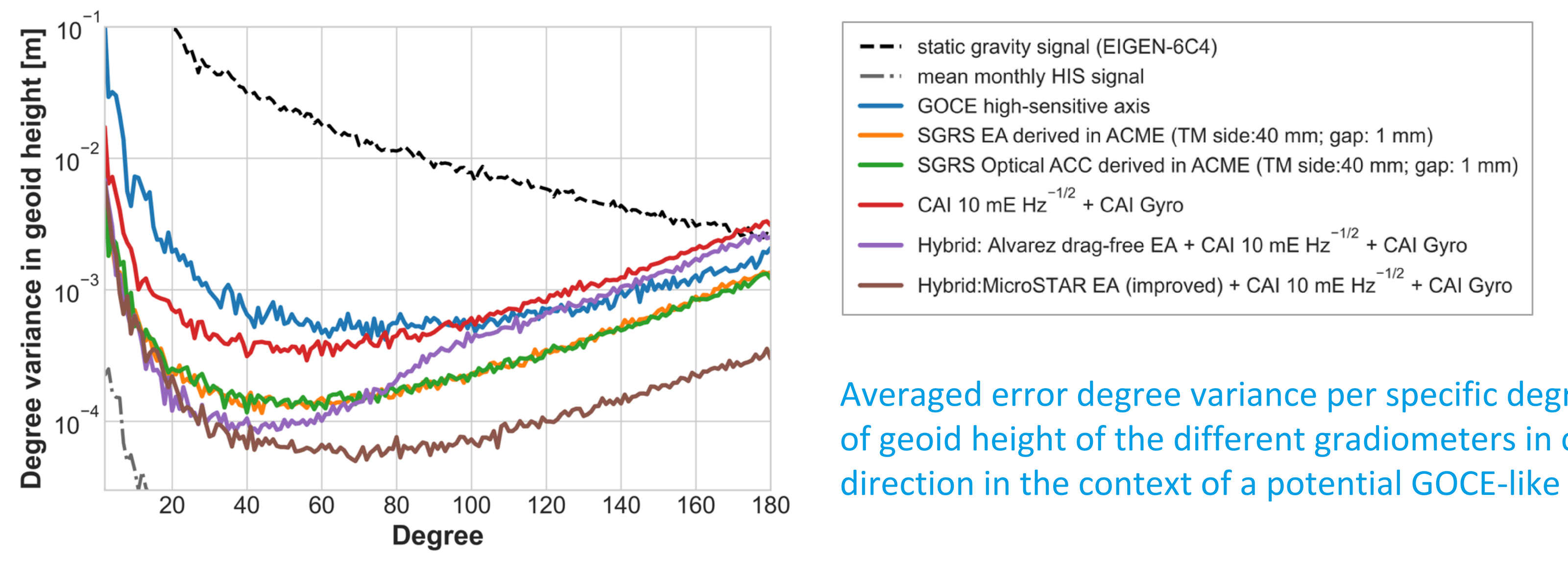
- Combination of novel ACCs from ACME with LRI 2030 shows significant improvement in gravity field recovery w.r.t. GRACE instruments (SuperSTAR EA with KBR)
- Performance of the Simplified gravitational reference sensor (SGRS) EA from ACME w.r.t. CAI and hybridized ACCs show similar level of accuracy
- By utilizing novel instruments, it is possible to avoid filtering or post-processing of the gravity field models from GRACE-like polar pair missions



Left: Comparison of the ASD sensitivities of accelerometers for current instruments and anticipated concepts
Right: Averaged error degree variance per specific degree in terms of geoid height of the different on-board accelerometers in the context of GRACE-like missions

5. Gravity field recovery | Cross-track gradiometry

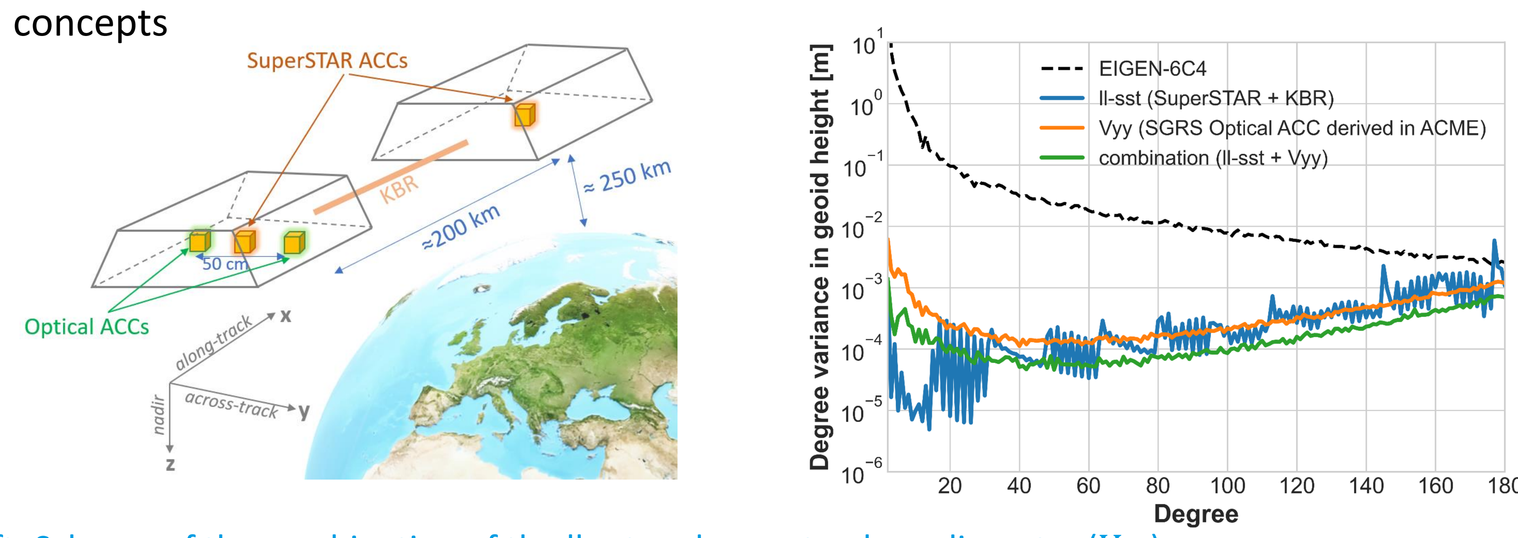
- Modelled gradiometers from ACME (both EA and optical) show significant improvement w.r.t. GOCE high-sensitive gradiometer
- Hybridized quantum gradiometers show the best performance up to degree 80



Averaged error degree variance per specific degree in terms of geoid height of the different gradiometers in cross-track direction in the context of a potential GOCE-like mission

6. Gravity field recovery | ll-sst + cross-track gradiometry

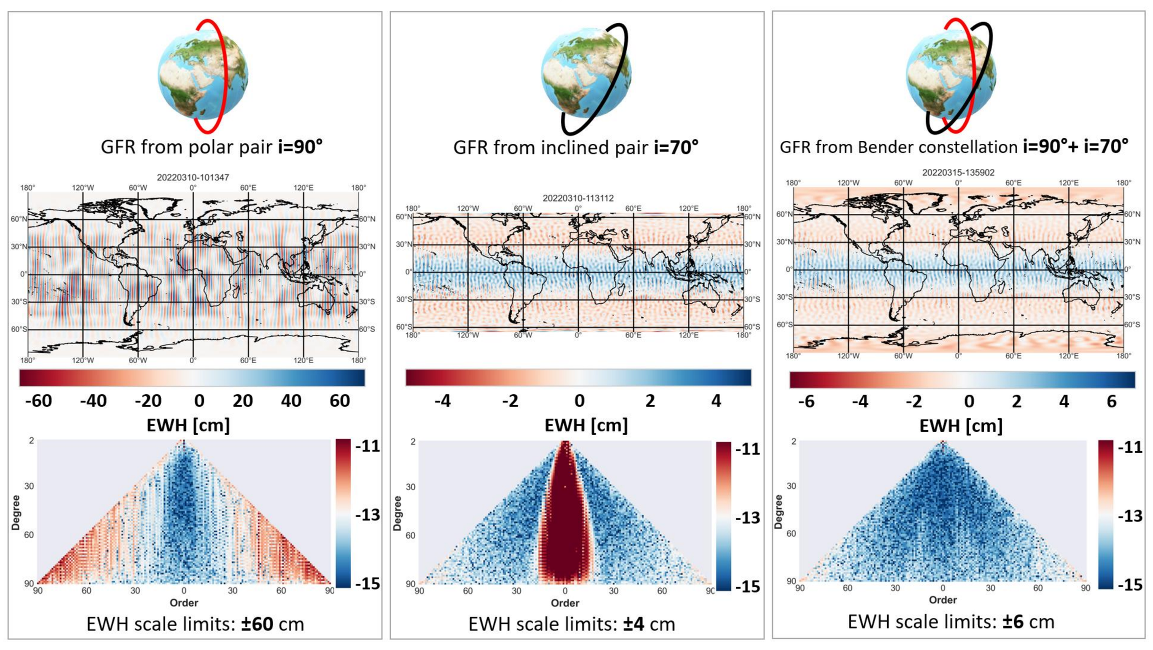
- North-South striping effect reduced
- Benefit from advantages of GRACE (temporal gravity signals) and GOCE (static gravity signals) concepts



Left: Scheme of the combination of the ll-sst and cross-track gradiometry (V_{yy});
Right: Averaged error degree variance per specific degree in terms of geoid height w.r.t. EIGEN-6c4

7. Gravity field recovery | Bender constellation

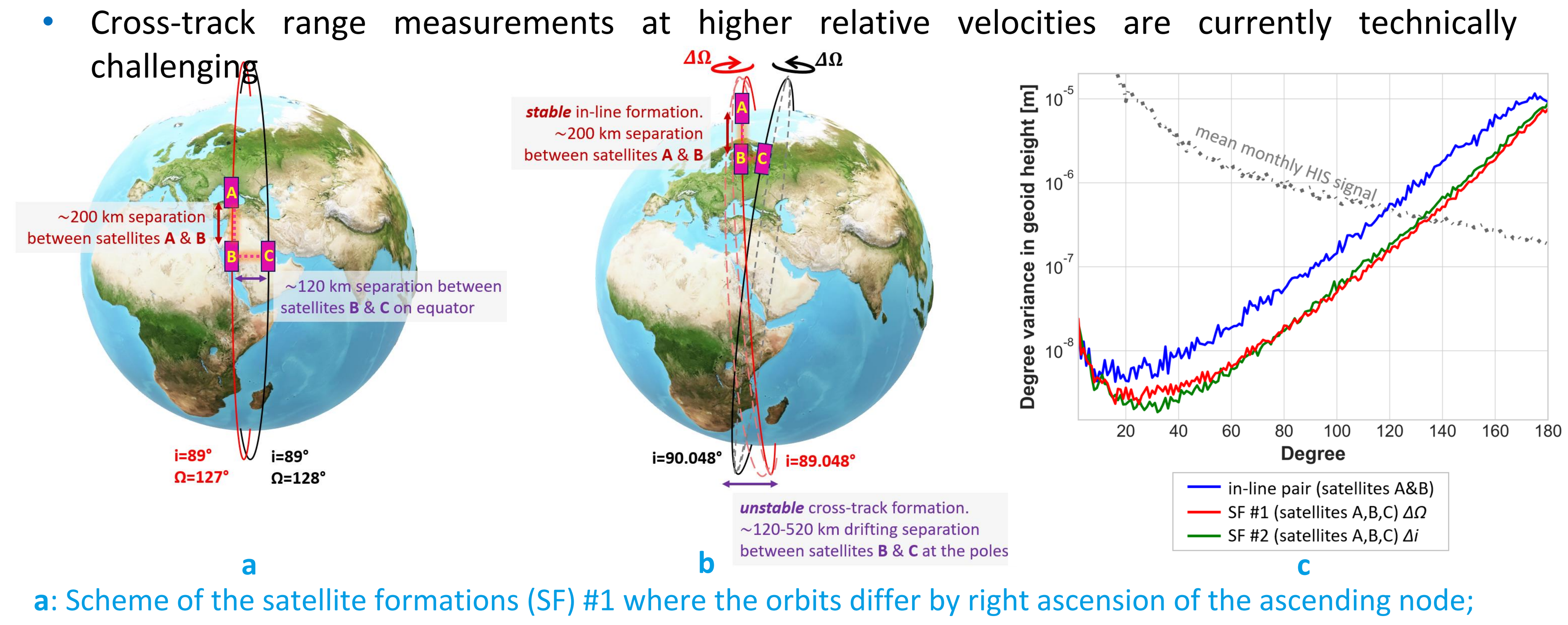
- Bender constellation will significantly improve the accuracy of the GFR solutions on global scale w.r.t. GRACE-FO current outputs



Recovered gravity fields (raw data, without post-processing and filtering) from Bender constellation.
Left: from polar satellite pair; Middle: from inclined orbit;
Right: combination from 2 satellite pairs w.r.t. EGM2008 in terms of EWH

8. Gravity field recovery | Novel satellite formations

- Both novel satellite formations show an improvement in retrieving the gravity field w.r.t. in-line pair solely
- Cross-track range measurements at higher relative velocities are currently technically challenging



a: Scheme of the satellite formations (SF) #1 where the orbits differ by right ascension of the ascending node;
b: Scheme of the satellite formations (SF) #2 where the orbits differ by inclination;
c: Averaged error degree variance per specific degree in terms of geoid height of the in-line pair solely (blue) and from combined SF #1 (red) and SF #2 (green)

Acknowledgments

DFG: TerraQ (ID: 434617780 – SFB 1464)

CARIOQA-PMP (ID: 101081775)

DLR Q-BAGS (ID: 50WM2181) & DLR QUANTGRAV (ID: 50EE2220B)

9. Conclusions

- Successful forward and backward modelling of various one-month gravimetric mission scenarios
- Showed that modeled ACCs and gradiometers based on optical test mass sensing provide a similar performance as the novel concepts from other research groups, including CAI and hybridized sensors
- Showed that novel future gravimetry missions concepts:
  - *ll-sst + cross-track gradiometry*
  - *Bender constellation*
  - *in-line + cross-track formation*

  allow to improve the recovered gravity field models
- Effects due to insufficient background modelling have been neglected as the main goal of the study: evaluate the benefit of the novel sensors' and concepts'

References

1. Alvarez, A. D., Knudtson, A., Patel, U. et al. (2022). A simplified gravitational reference sensor for satellite geodesy. Journal of Geodesy, 96(10). doi:10.1007/s00190-022-01659-0.
2. Armano, M., Audley, H., Baird, J. et al. (2018). Beyond the required LISA free-fall performance: New LISA Pathfinder results down to 20 mHz. Physical review letters, 120(6), 061101. doi:10.1103/PhysRevLett.120.061101
3. Beaufils, Quentin, et al. "Rotation related systematic effects in a cold atom interferometer onboard a Nadir pointing satellite." npj Microgravity 9.1 (2023): 53.
4. Darbeheshti, N., Wegener, H., Müller, V. et al. (2017). Instrument data simulations for GRACE Follow-On: observation and noise models. Earth System Science Data, 9(2), 833–848. doi:10.5194/essd-9-833-2017
5. Douch, K., Müller, J., Heinzel, G. et al. (2017). Recovering the time-variable gravitational field using satellite gradiometry: requirements and gradiometer concept. In EGU General Assembly Conference Abstracts EGU General Assembly Conference Abstracts (p. 14875)
6. Marque, J.-P. et al. (2010). Accelerometers of the GOCE Mission: Return of Experience from One Year of In-Orbit. In ESA Living Planet Symposium
7. Naeimi, M., & Flury, J. (2017). Global gravity field modeling from satellite-to-satellite tracking data. Springer.
8. Pail, R., Bingham, R., Braitenberg, C. et al. (2015). Science and user needs for observing global mass transport to understand global change and to benefit society. Surveys in Geophysics, 36(6), 743–772. doi:10.1007/s10712-015-9348-9
9. Touboul, P., Foulon, B., Christophe, B. et al. (2012). CHAMP, GRACE, GOCE instruments and beyond. In S. Kenyon, M. C. Pacino, & U. Marti (Eds.), Geodesy for Planet Earth (pp. 215–221). Berlin, Heidelberg: Springer Berlin Heidelberg volume 136 of International Association of Geodesy Symposia. doi:10.1007/978-3-642-20338-1
10. Weber, W. J., Bortoluzzi, D., Bosetti, P. et al. (2022). Application of LISA gravitational reference sensor hardware to future intersatellite geodesy missions. Remote Sensing, 14(13), 3092. doi:10.3390/rs14133092.
11. Wöske, F. (2021). Gravity Field Recovery from GRACE Satellite Data and Investigation of Sensor, Environment and Processing-Option Influences by Closed Loop Mission Simulation. Ph.D. thesis

www.ife.uni-hannover.de
Alexey Kupriyanov
kupriyanov@ife.uni-hannover.de