Albert Einstein Institut
Institut für Gravitationsphysik
Leibniz Universität Hannover

PRECISION LASER BEAM POINTING: ROLE OF FINE STEERING MIRROR IN GRACE-FO AND BEYOND

Reshma Sudha, Vitali Müller, Malte Misfeldt and Gerhard Heinzel
Max-Planck Institute for Gravitational Physics(AEI), Hannover
Institut für Gravitationsphysik, Leibniz Universität Hannover

Introduction

-The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission, launched in 2018, is the first mission to carry a Laser Ranging Interferometer (LRI) to accurately measure distance variations between the twin satellites, enabling a more accurate understanding of Earth's gravitational field.

- One of the critical components of the LRI is the **Fast Steering Mirror (FSM)** manufactured by Airbus Defence and Space GmbH responsible for directing the laser beams accurately from one spacecraft to the other. It utilizes voice-coil based actuators with Eddy current sensors for position sensing from Kaman Aerospace Corp.

- Two phases of operation of the mission where FSM's operation is critical. **Acquisition phases:** the satellites scan the uncertainty cone to establish the link and **Science phase**: where Differential Wavefront Sensing(DWS) is used to control the mirror. For future missions like GRACE-Continuity(GRACE-C) and Next Generation Gravity Mission(NGGM), the FSM is identified as a potential single point of failure with two failure modes: **Coil failure** and **Position Sensing Signal(PSS) failure**.

Fig.1 DWS principle
The tip/tilt misalignments between the beams can be computed.

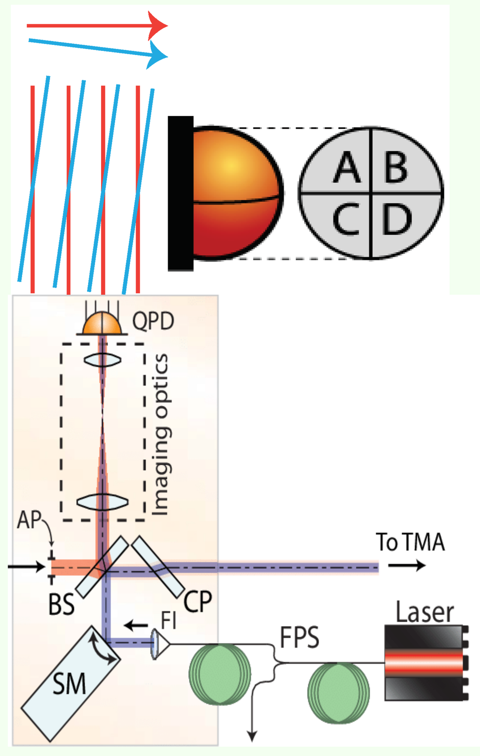


Fig.2 FSM Setup in LRI. Schematic of the present optical bench design.

FSM tesbed

An **FSM test bed** in AEI lab was used for tests and analysing FSM behaviour. The components include: an LRI-like FSM with Kaman KD5100(PSS), Autocollimator, laser beam(1064nm) with QPD, AEI-built current driver and PSS feedback controller.

Autocollimator(25Hz) not enough to resolve resonance oscillations of FSM. Hence, laser beam and PSS feedback is utilised.

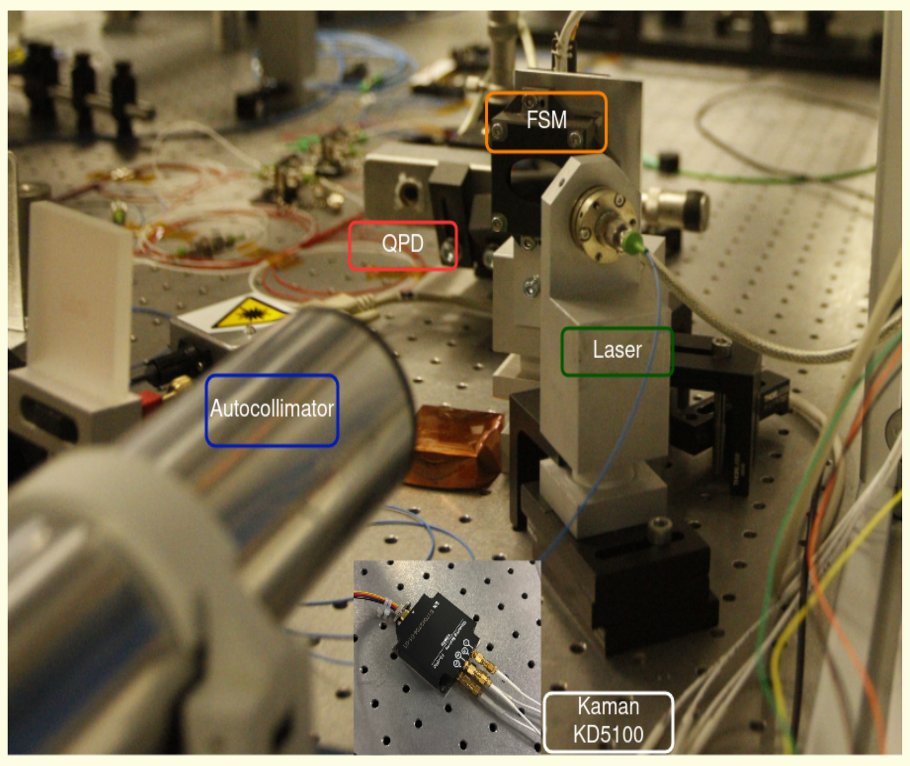
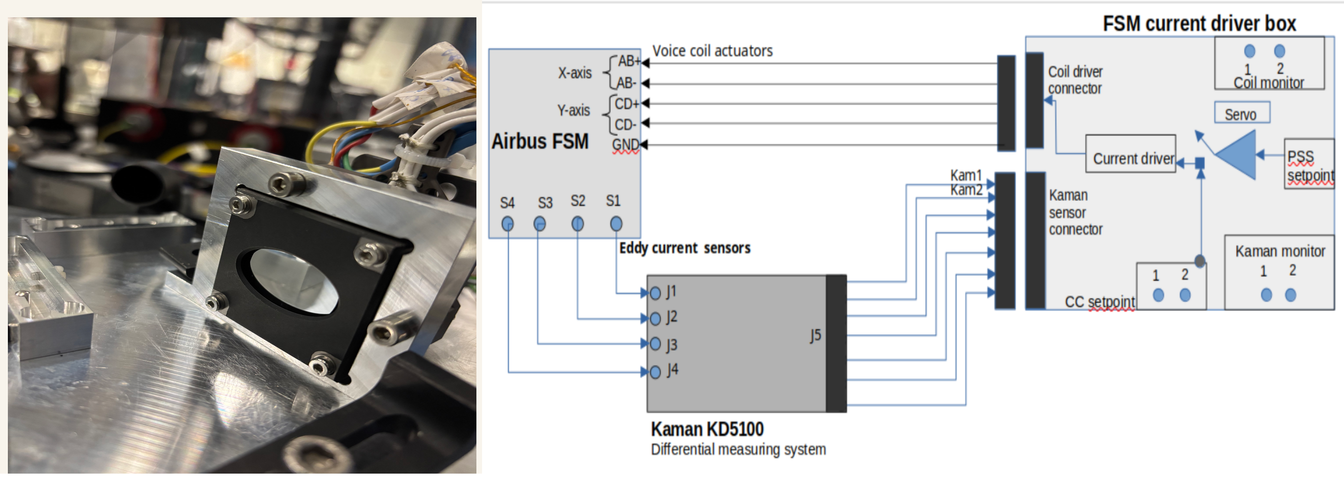


Fig.3 FSM Tetbed

FSM control loops

The Digital Phase Locked Loop(DPLL) tracks the phase of the incoming beatnote signal from QPD. The phase tracked from 4 quadrants are utilised to compute the DWS signal.
The closed loop operation of FSM involves the servo controller in two nested stages.
Inner control loop: Optical Bench Electronics(OBE) with the Kaman sensor axes as setpoints to stabilise the mirror orientation. **Outer control loop**: Phasemeter(PM) with the DWS tip and tilt setpoints. In Fig. 4, the red circles denote the failure points and the **bypass PID controller** enables open-loop operation.

Fig.4
Left: Voice-coil based FSM used in our lab.
Right: FSM connection to current driver and PSS controller



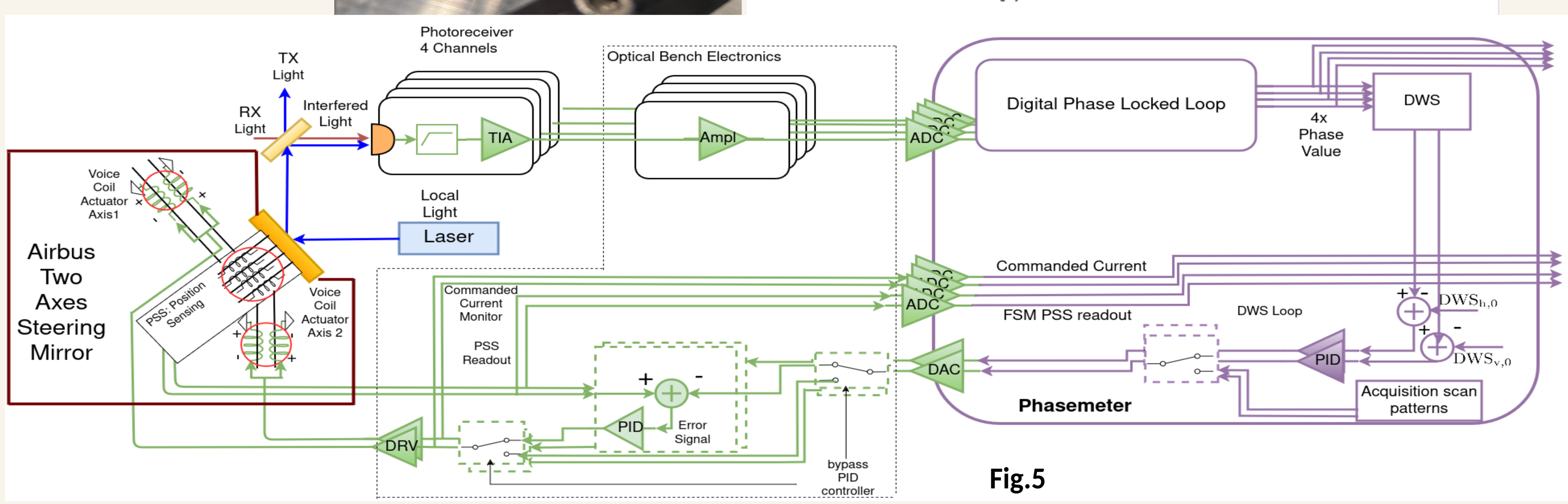


Fig.5
LRI FSM control and readout

Mitigation of PSS failure

Currently, the steering mirror control and readout utilises the two stage control to compute the error signal for the closed loop operation of FSM.

The PSS failure of FSM can be compensated by disabling the PSS and inner control loop, and driving the FSM directly from the DWS error signal(**open-loop operation**). This accentuates mechanical resonance oscillations at 40Hz and 42Hz with 1.4-2.8 μrad-pk peak height for 1μVpk/rtHz input noise to the current driver. This leads to constraints on the Digital to Analog Converter(DAC) card and electronics, but still within the allowable optical jitter of 15-20μrad-pk [all voltage levels, specific to our current driver box]. The typical open-loop transfer function with resonances at 40 and 42Hz is shown in Fig. 6. Q factor estimated for a step response with analytical pole-zero gain model is comparable to step response to the current driver(Fig. 7).

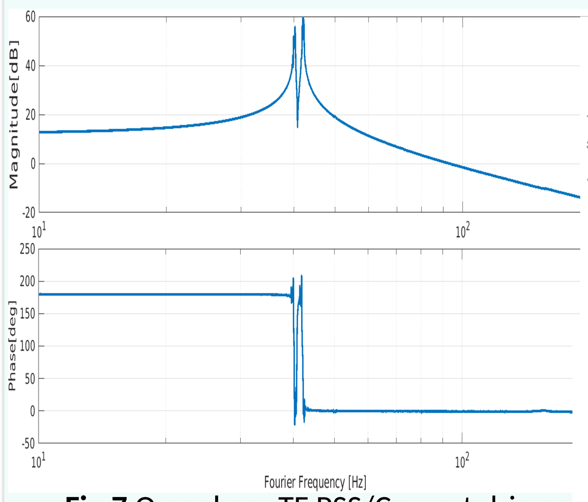


Fig.7 Open loop TF PSS/Current driver

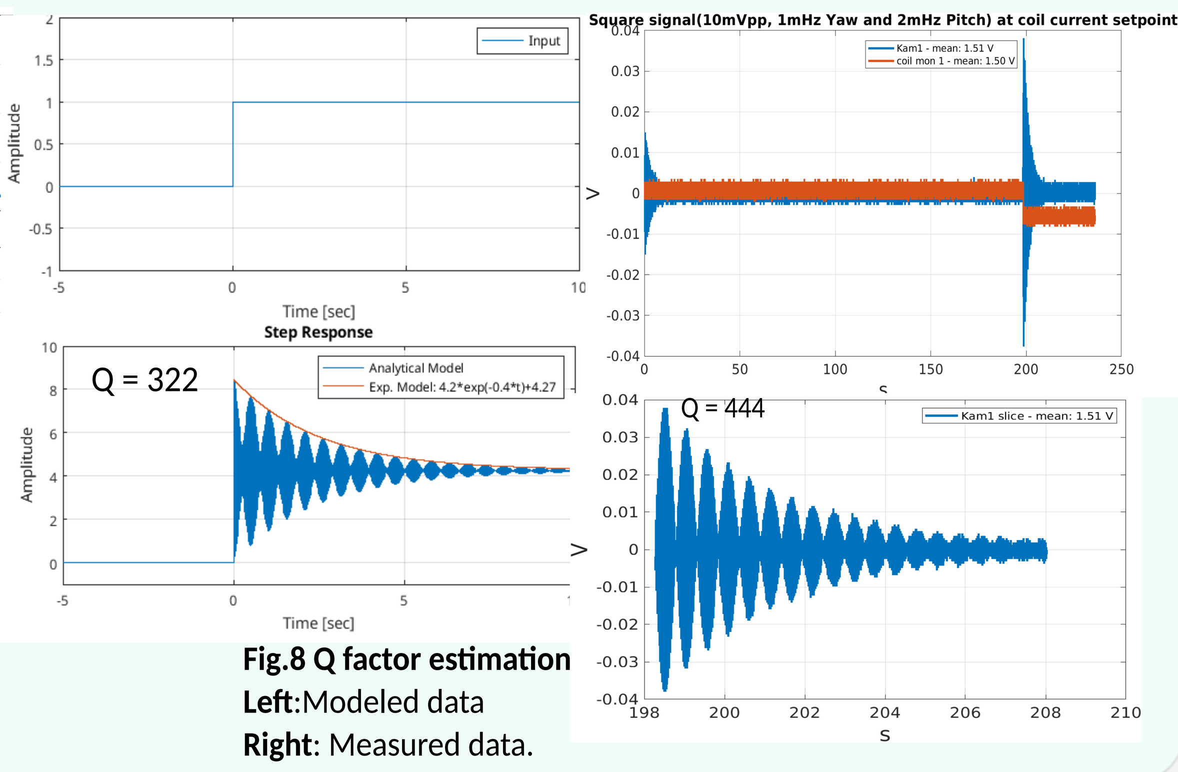
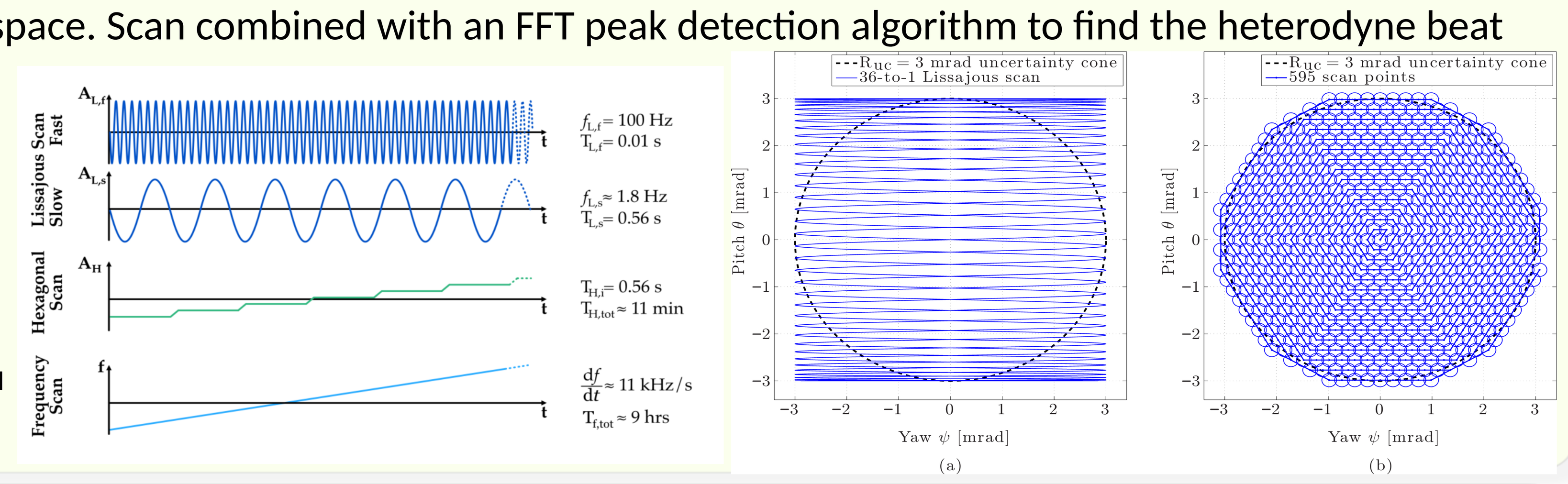


Fig.8 Q factor estimation
Left:Modeled data
Right: Measured data.

Acquisition Scans

To acquire **laser link after launch**, simultaneous scan of 5 degrees of freedom: fast spatial scan of FSM(± 3 mrad in pitch/yaw for each laser beam) and frequency scan(± 1 GHz for the frequency difference between the two lasers) [Outer DWS loop inactive]. Re-acquisition scan done with reduced uncertainty space. Scan combined with an FFT peak detection algorithm to find the heterodyne beat note.

Fig.6
Initial Spatial scan(Lissajous and Hexagonal) and frequency scan.



Mitigation of Coil Axis Failure

The FSM module has two voice coil actuators per axis which are usually operated in parallel. To verify the redundancy, the coils were manually connected to a switch to enable operation of individual coils per axis. The inactive coils were checked in open, short and grounded connections. The **redundancy tests** presented promising results indicating stable operation of the FSM by activating one coil per axis, in case of a coil failure.

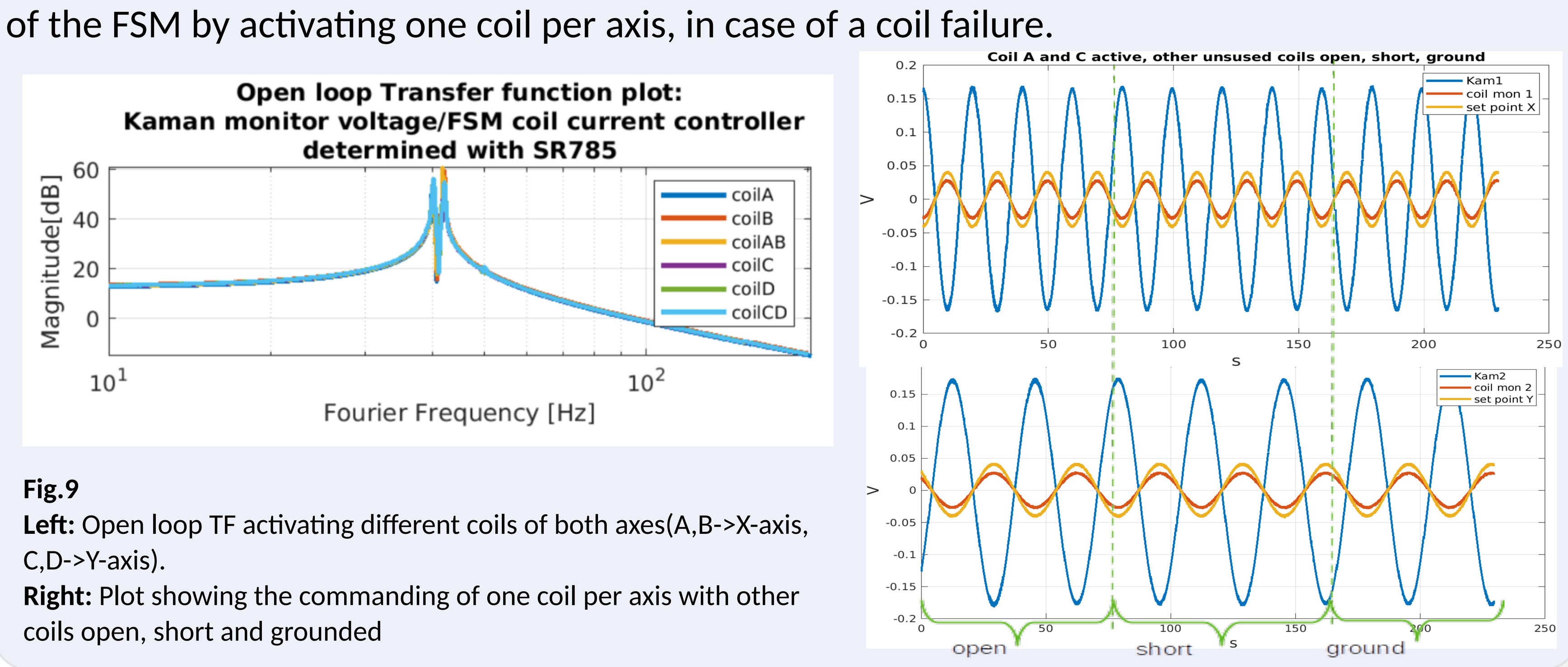


Fig.9
Left: Open loop TF activating different coils of both axes(A,B->X-axis, C,D->Y-axis).
Right: Plot showing the commanding of one coil per axis with other coils open, short and grounded

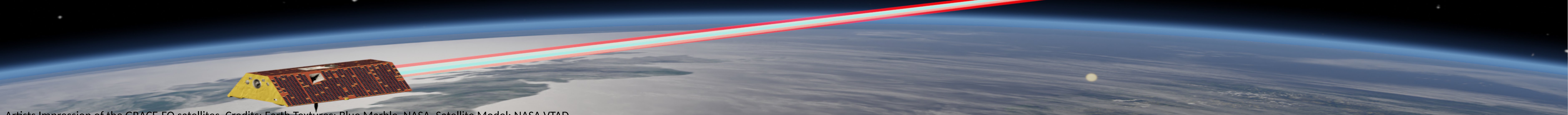
Conclusion and Outlook

>The experimental investigations conducted with our FSM testbed are important for the Grace-C and NGGM missions. The results show that **redundancy of actuator** coils are **achievable** and that **mitigation** of **PSS failure** is possible.
>Further tests need to be conducted to optimise the laser link acquisition scans with the open loop operation of FSM to take into account the resonance oscillations.
>The **voltage noise** is an important parameter affecting the resonance oscillations of FSM and in turn the pointing accuracy. This need to be investigated further with the **OBE**.

Contact: reshma.krishnan.sudha@aei.mpg.de

Further Reading

- **Heinzel et.al.**, Laser ranging interferometer for GRACE follow-on. International Conference on Space Optics—ICSO 2012
- **Abich et.al** , GRACE-Follow On Laser Ranging Interferometer: German contribution. Journal of Physics, DOI 10.1088/1742-6596/610/1/012010
- **Müller Vitali**, PhD Thesis, Design Considerations for Future Geodesy Missions and for Space Laser Interferometry. Gottfried Wilhelm Leibniz Universität Hannover
- **D. Wuchenich et.al.**, Laser link acquisition demonstration for the GRACE Follow-On mission. Opt. Express 22, 11351-11366 (2014)



Artists Impression of the GRACE-FO satellites. Credits: Earth Textures: Blue Marble, NASA. Satellite Model: NASA VTAD