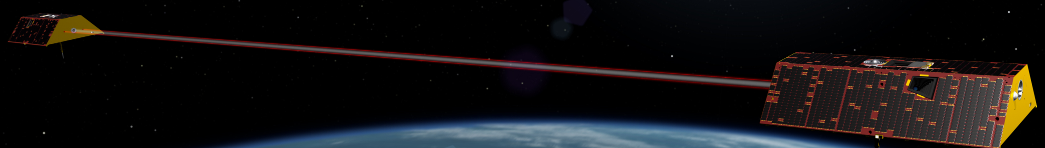
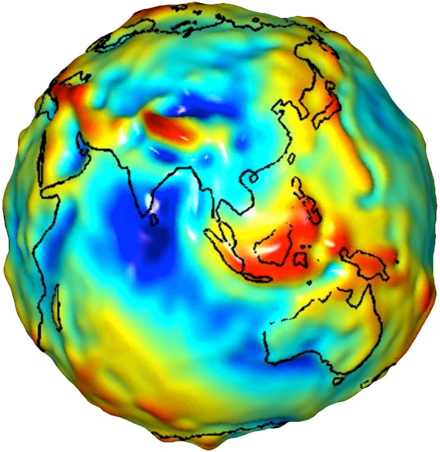


The first interspacecraft laser ranging interferometer on GRACE-FO and conclusions for future gravity missions

Malte Misfeldt, Gerhard Heinzel for the LRI collaboration

Max-Planck Institute for Gravitational Physics, Hannover
Institut für Gravitationsphysik, Leibniz Universität Hannover

Second European Physical Society Conference on Gravitation: Measuring Gravity



The **geoid is a hypothetical construct** representing a surface, on which all points share the **same gravitational potential**.

If Earth was completely covered with water (and without any non-gravitational forces), it would look like the geoid.

The geoid **changes when mass redistributes**, e.g. when rocks move (earthquakes), ice melts (pole caps, glaciers) or water accumulates (rain, monsoon).

Image Credit: CSR, UT

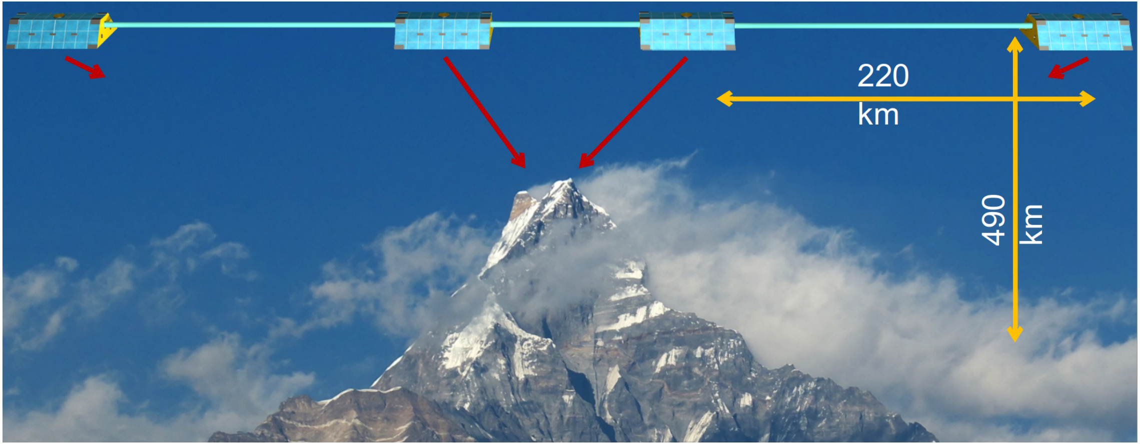
Introduction
Geodesy Missions

Space-borne geodesy missions for determining the geoid have a history!

- CHAMP (D/US, 2000-2010):
  1 satellite, orbit tracking
- GRACE (US/D, 2002-2017):
  2 satellites, microwave ranging
- GOCE (ESA, 2009-2013):
  1 satellite, 3-axis gradiometer
- GRAIL (US, 2011-2012):
  2 satellites, microwave ranging
- GRACE Follow-On (US/D, 2018-today),
  2 satellites, microwave **and laser ranging**

Image Credits: GFZ, NASA/JPL, ESA, DLR

Introduction
The GRACE Principle



With the GRACE missions, monthly snapshots of the Earth gravity field are taken.

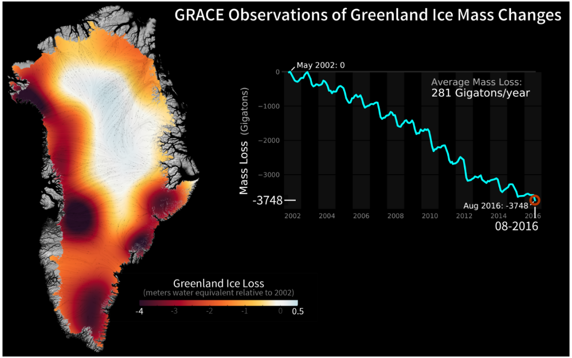
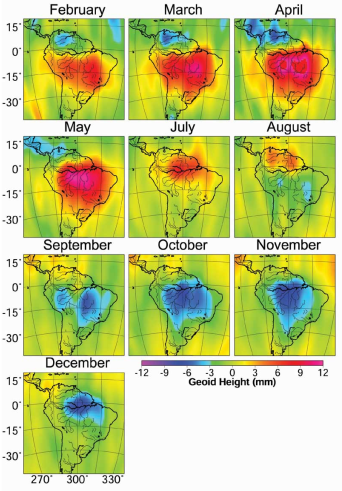
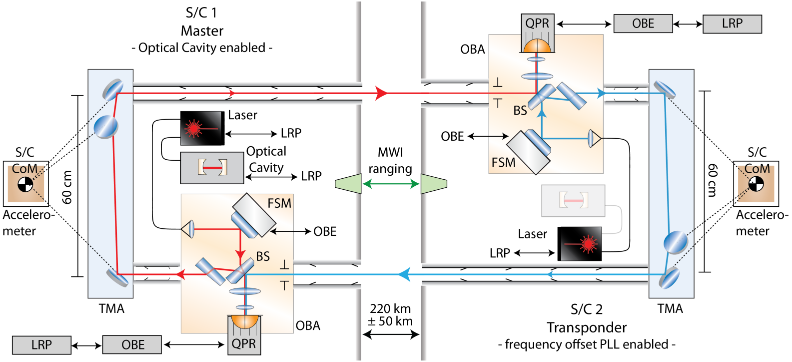


Image Credits: NASA/JPL



The LRI
Setup

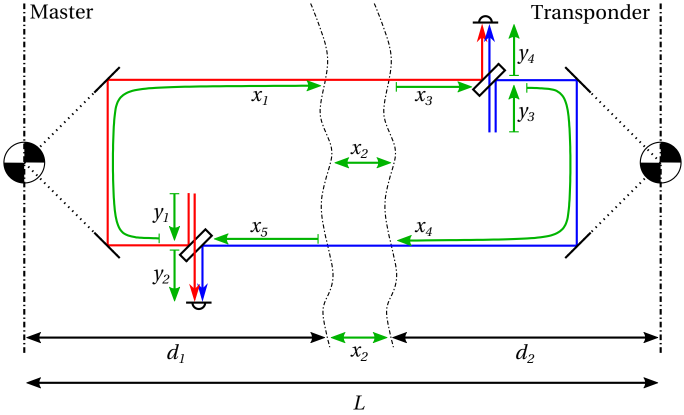


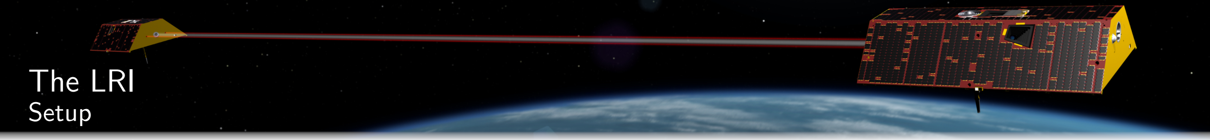
The LRI was developed in a US-German collaboration between AEI and NASA/JPL, including industrial partners STI, Airbus, . . .

Image Credit: Abich et al. [1]

The LRI measures twice the distance between the TMA vertex points, which are ideally located within the S/C CoM:

$$M = x_1 + x_2 + x_3 + x_4 + x_2 + x_5$$
$$= 2(d_1 + d_2 + x_2) = 2L$$

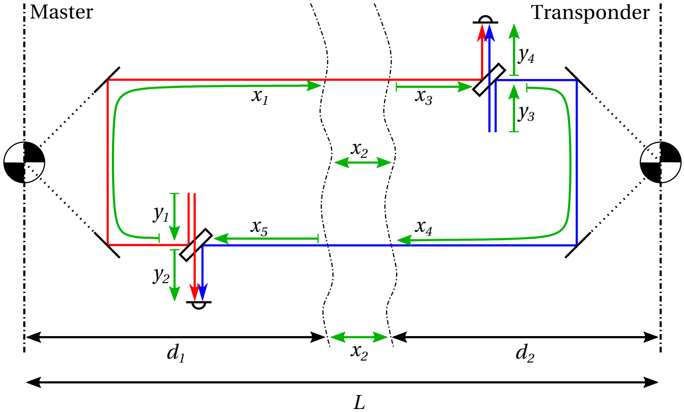




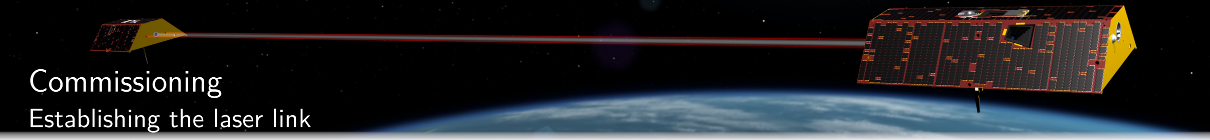
The LRI
Setup

The LRI measures twice the distance between the TMA vertex points, which are ideally located within the S/C CoM:

$$
\begin{aligned}
M &= x_1 + x_2 + x_3 + x_4 + x_2 + x_5 \\
&= 2(d_1 + d_2 + x_2) = 2L
\end{aligned}
$$



Challenge: How to establish the laser link?



Commissioning

Establishing the laser link

- Initially, the pointing of the individual LRI units is only known up within a certain tolerance: The laser beams do not point along the line-of-sight!
  - Alignment tolerances during integration
  - Shaking during rocket launch
  - Zero-g settling
  - ...
- The transponder's laser frequency must match the master's cavity within 16 MHz (limited by bandwidth of the photodetector)
- Thus, to acquire a Laser-Link between the two LRI units, 5 degrees of freedom (2 angles per S/C, 1 frequency (transponder)) need to meet a narrow range, all at once, in order to see a signal. This calibration is called **Initial Acquisition**

Commissioning

Initial Acquisition Scan Design

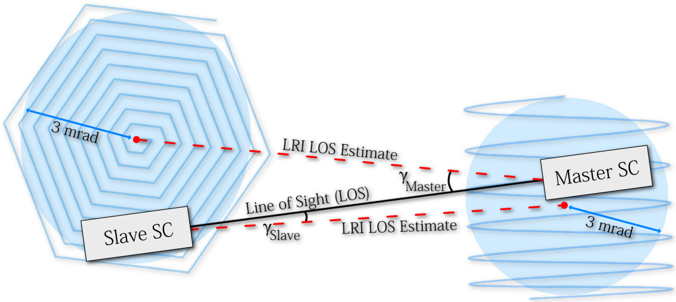


Image Credit: Koch et al. [2]

- Master: Slow Hexagon Pattern (10.5 min)
- Transponder: Fast Lissajous Pattern (0.5 s) and linear frequency ramp (9 hrs, 360 MHz)
- Continuous spectral evaluation of the photoreceiver signals: If the frequency-difference is within the bandwidth and the angles match, a peak in the spectrum is detected

- Back on Earth: Plenty of flashes!
- The center denotes the angular pointing offsets
- Starting from these offsets, a **Reacquisition Scan** with a smaller scan range is performed with autonomous transition into **science mode**.

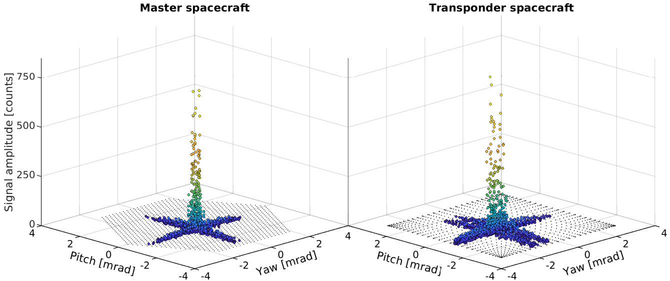


Image Credit: Abich et al. [1]

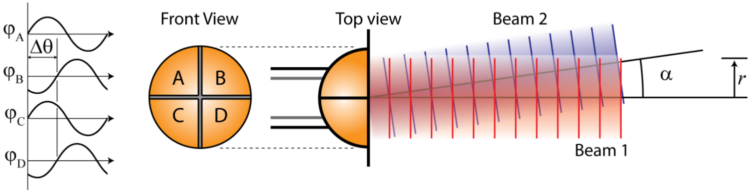
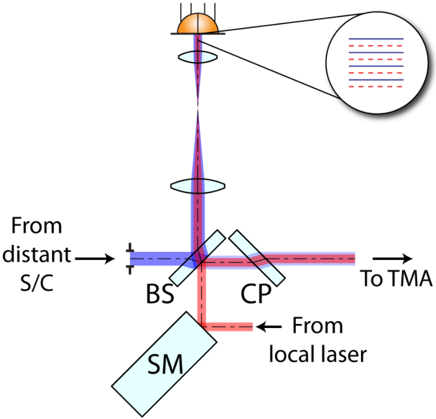


Image Credit: Sheard et al. [3]

- Using a multi-segment photodiode, relative alignment of the beams can be determined
- Relative beam tilts can be measured with high gain of 5000...20 000 rad/rad
- The LRI provides yaw and pitch angles (w.r.t. line of sight) with low noise, which could be used for improving the SCA or AOCS

Commissioning

Ensuring the alignment: Actuator

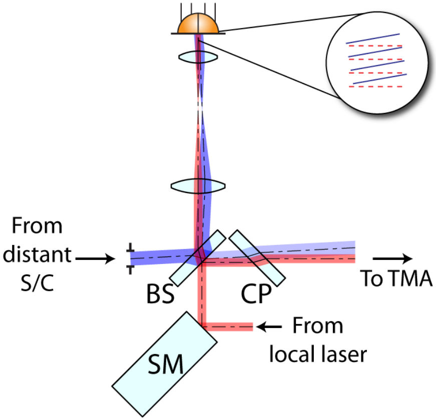


Transmit and received beam recombine on beam splitter and pass imaging optics. In nominal case, the beams are perfectly aligned.

Image Credit: Sheard et al. [3]

Commissioning

Ensuring the alignment: Actuator

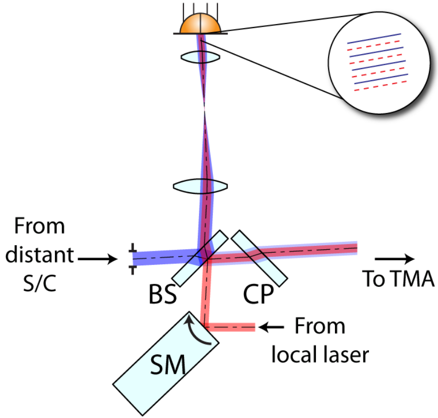


Transmit and received beam recombine on beam splitter and pass imaging optics. In nominal case, the beams are perfectly aligned.

S/C rotations cause the incoming beam to be misaligned w.r.t. the local beam ⇒ Non-zero DWS signal, reduction of signal contrast and misaligned outgoing beam.

Image Credit: Sheard et al. [3]

Ensuring the alignment: Actuator



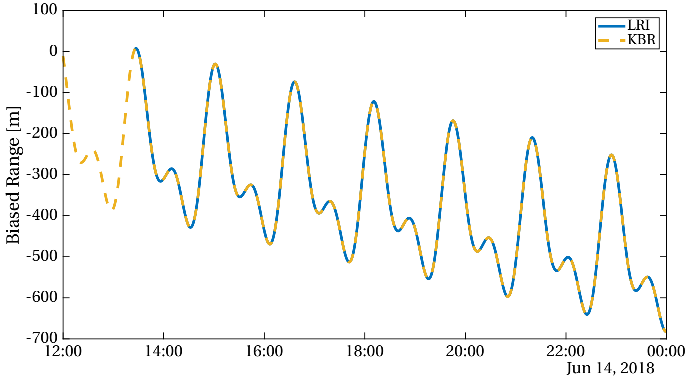
Transmit and received beam recombine on beam splitter and pass imaging optics. In nominal case, the beams are perfectly aligned.

S/C rotations cause the incoming beam to be misaligned w.r.t. the local beam $\Rightarrow$ Non-zero DWS signal, reduction of signal contrast and misaligned outgoing beam.

Closing the loop between DWS readout and steering mirror position zeros the DWS signal. Received and transmit beam are parallel again.

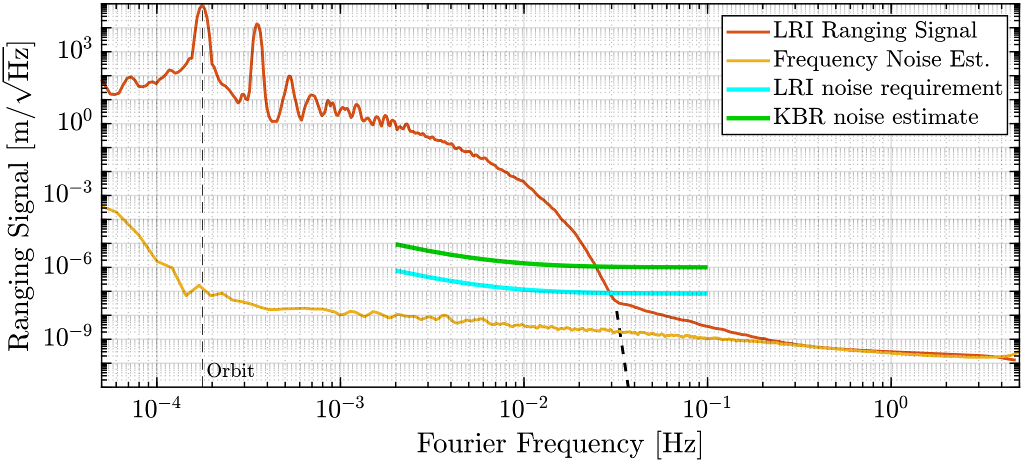
Image Credit: Sheard et al. [3]

In-Orbit Performance
Time Domain

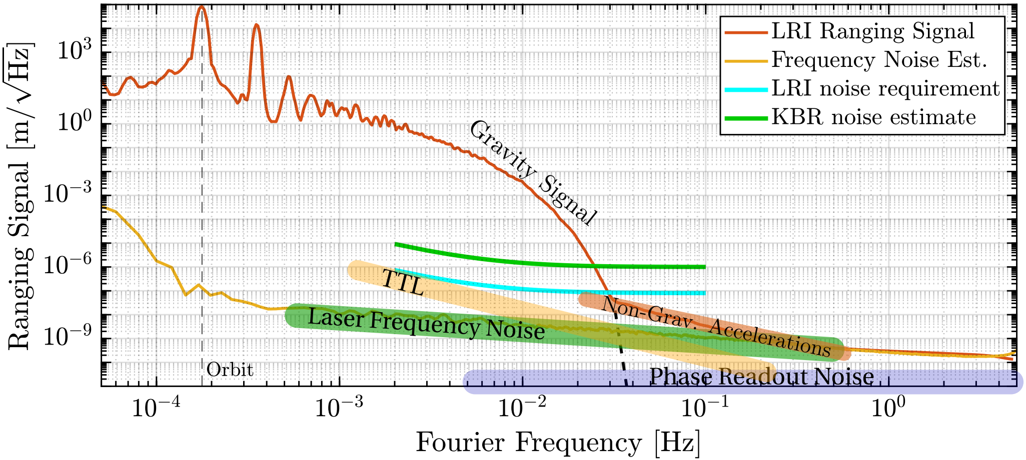


- The LRI went into science mode on first attempt (2018-06-14 13:23:51 UTC)
- It stays in lock for hundreds of orbits without interruption

In-Orbit Performance
Frequency Domain



In-Orbit Performance
Frequency Domain



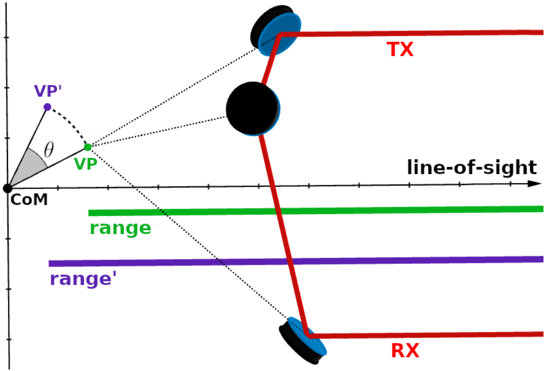
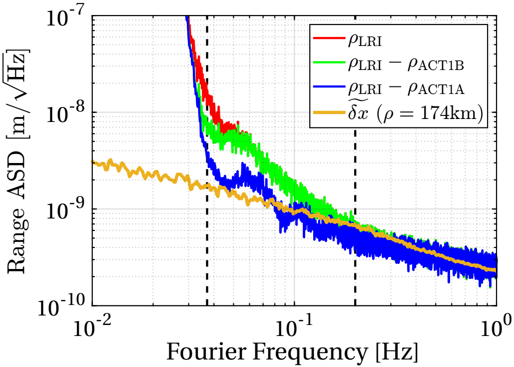


Image Credit: Wegener et al. [4]

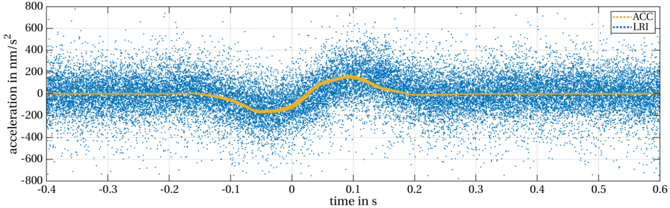
- Due to residual integration errors and CoM-to-Vertex offsets of the TMA, spacecraft rotations alter the range measurement.
- The linear coupling factors [units: μm/rad] can be determined using CoM calibration maneuvers. They are within the requirements for all three axis roll, pitch and yaw
- Bonus: Pitch and Yaw coupling factors are equivalent to CoM-VP offset, thus LRI can help to track the S/C CoM

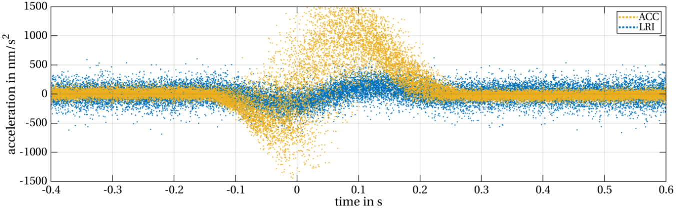
In-Orbit Performance
Non-Gravitational Accelerations

- In the frequencies above the gravity signal, an unexpected deviation from the laser frequency noise is observed
- Investigations showed that this arises from linear accelerations, e.g. solar radiation pressure and attitude thrusters
- It is possible to remove these unintended effects from the range



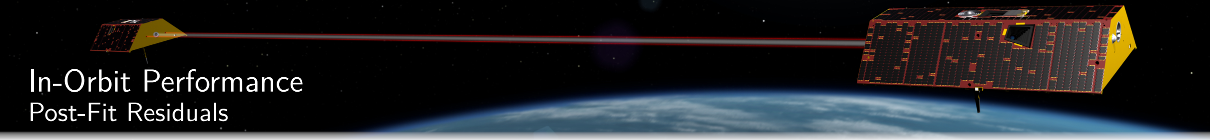
In-Orbit Performance
Non-Gravitational Accelerations





- Attitude control thruster induce not only rotations but also linear accelerations
- The LRI is able to resolve these (only in LoS)
- This new dataset allows further calibration of the thrusters
- Top: Yaw- thruster events, Bottom: Roll+ thruster events

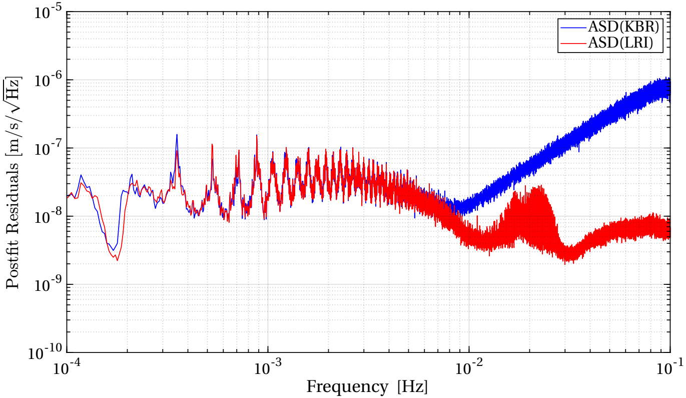
Image Credit: Stuhrmann [5]



In-Orbit Performance
Post-Fit Residuals

- "post-fit": Residual signal after gravity field recovery
- Lower frequencies: Background modeling, Aliasing and Accelerometer noise dominate the residuals
- The LRI has less noise above 8 mHz, revealing a mis-modeling in the background models

(Ghobadi-Far et al. [6])



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Post-Fit Residuals

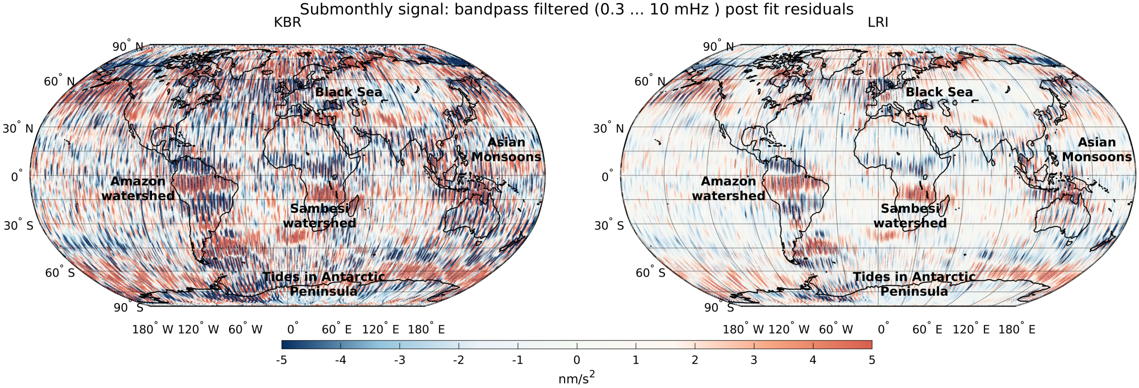
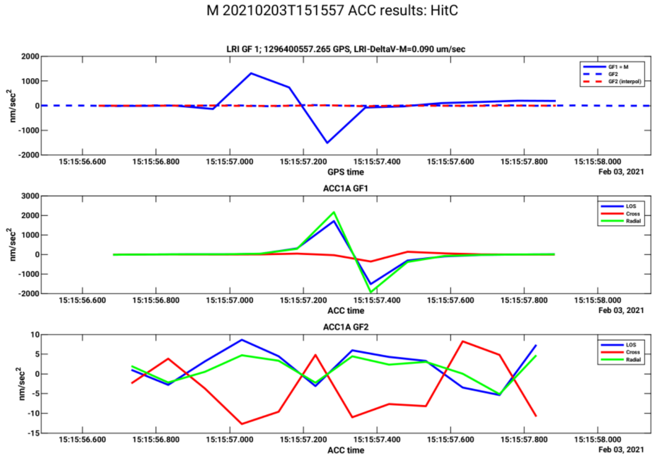


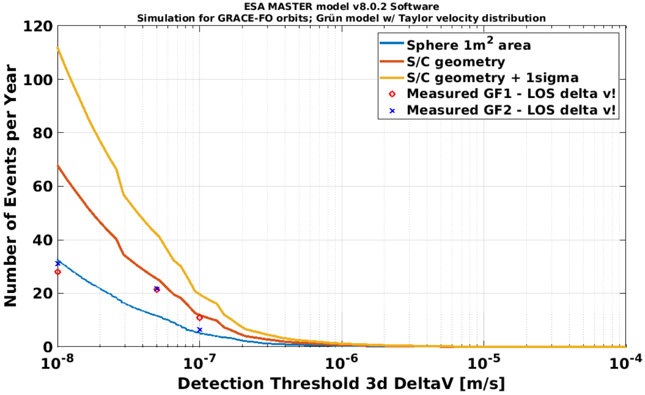
Image Credit: Max-Planck Institute for Gravitational Physics (Albert Einstein Institute) [7]

In-Orbit Performance
Other scientific outputs



- The high sensitivity of the LRI can resolve tiny disturbances (at frequencies higher than the gravity signal)
- Some of these disturbances correlate with spikes in the ACC (LoS direction)
- The LRI is able to detect Δv-changes, likely caused by micro-meteorite impacts (10 µg at 15 km/s)
- Roughly 30 Events per S/C per year

In-Orbit Performance
Other scientific outputs



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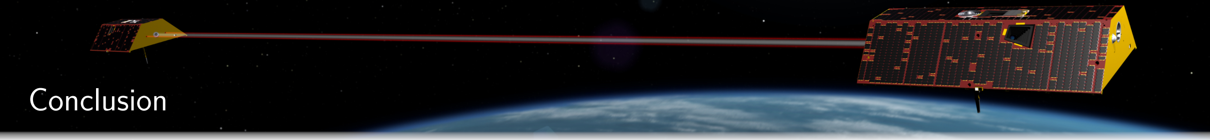


Conclusion

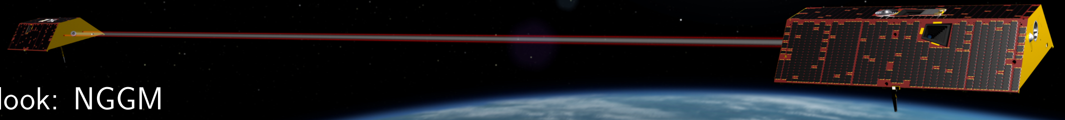
The LRI provides **precise ranging data** with a noise level as small as $200\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at a frequency of $5\,\mathrm{Hz}$.

Long uninterrupted measurements, e.g. for more than 106 days, which is approximately 1650 orbital revolutions.

No degradation of LRI data streams was observed so far. The LRI should provide high quality ranging and attitude data in the next years.

The low LRI noise enables new insights like micro-meteorites or into thruster characterization.

The LRI ranging data does not limit the Earth gravity field recovery.



Outlook: NGGM

The LRI proved that inter-satellite laser ranging is ready for being used, e.g. in NGGM or LISA.

Different concepts using laser istruments as primary ranging instrument are being studied by ESA. Ensuring the lifetime over many years and full redundancy requires some more effort.

Possible Improvements

- Dedicated Acquisition Sensor
- Feedback of LRI pointing information into attitude control, which reduces tilt-to-length noise
- Mitigation of thruster-induced micro-shocks, especially of Roll-thruster, in order to avoid phase jumps

Contact Information

Feel free to ask questions!

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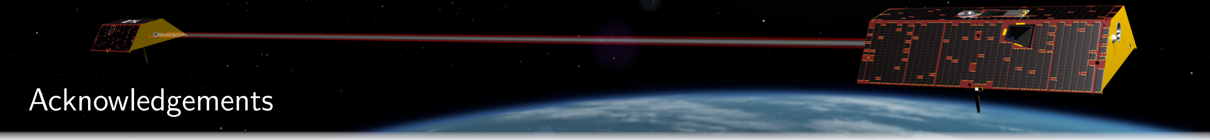
Hannover - Germany



Acknowledgements

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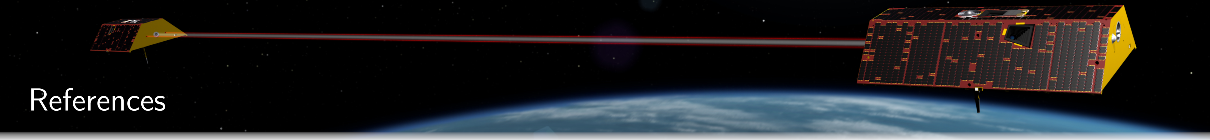

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[1] Klaus Abich et al. “In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer”. In: *Physical Review Letters* 123.3 (July 2019). DOI: 10.1103/physrevlett.123.031101.

[2] Alexander Koch et al. “Line of sight calibration for the laser ranging interferometer on-board the GRACE Follow-On mission: on-ground experimental validation”. In: *Opt. Express* 26.20 (Oct. 2018), pp. 25892–25908. DOI: 10.1364/OE.26.025892.

[3] B. S. Sheard et al. “Intersatellite laser ranging instrument for the GRACE follow-on mission”. In: *Journal of Geodesy* 86.12 (Dec. 2012), pp. 1083–1095. ISSN: 1432-1394. DOI: 10.1007/s00190-012-0566-3.

[4] Henry Wegener et al. “Tilt-to-Length Coupling in the GRACE Follow-On Laser Ranging Interferometer”. In: *Journal of Spacecraft and Rockets* (July 2020), pp. 1–10. DOI: 10.2514/1.a34790.

[5] David Stuhrmann. “Characterization of Attitude Thruster within GRACE Follow-On Laser Ranging Interferometer Data”. Bachelor’s Thesis. Institut für Gravitationsphysik, Leibniz Universität Hannover, Dec. 10, 2020.

[6] Khosro Ghobadi-Far et al. “GRACE Follow-On Laser Ranging Interferometer Measurements Uniquely Distinguish Short-Wavelength Gravitational Perturbations”. In: *Geophysical Research Letters* 47.16 (Aug. 2020). DOI: 10.1029/2020gl089445.

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