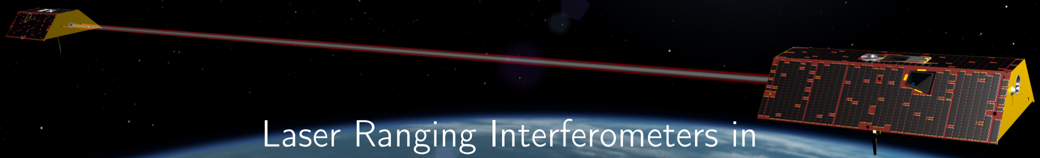

Laser Ranging Interferometers in GRACE-FO and for NGGM - Status

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EGU General Assembly 2022

Image Credit: NASA/JPL-Caltech

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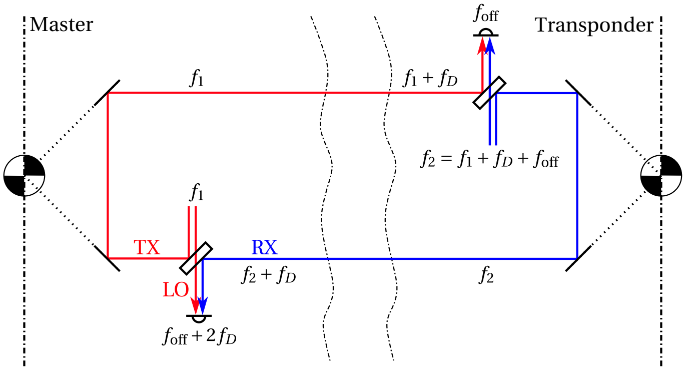
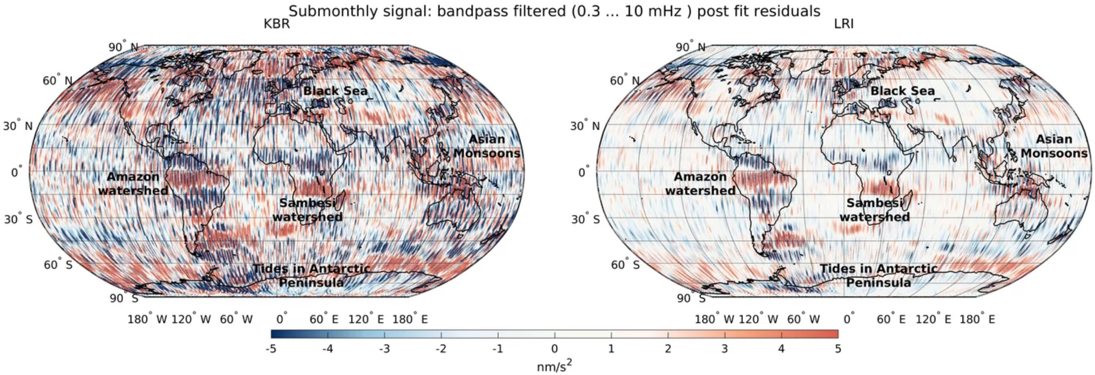
- LRI Working Principle
- LRI Measurements
- Recent/Planned LRI Activites
- Concept Design: LTI for NGGM/MCM/GRACE-I
- Conclusion

LRI Working Principle

- The LRI forms the very first laser interferometer operated between two seperate spacecraft [1, 11]
- The measured signal on the **master side contains the desired ranging variations**
- On the transponder side, the received light is amplified while maintaining the phase information (frequency offset digital phase-locked loop)

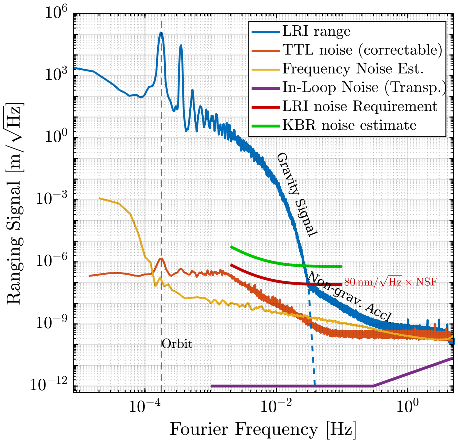


LRI Measurements
Postfit Residuals



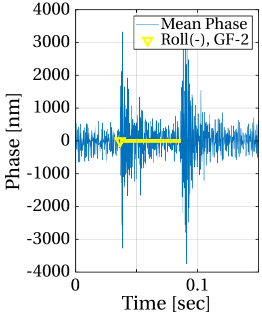
LRI and KBR show same signal (see e.g. Amazon watershed), but **LRI has higher SNR / lower noise** (especially over the oceans) Image Credit: [7]

LRI Measurements
Amplitude Spectral Density



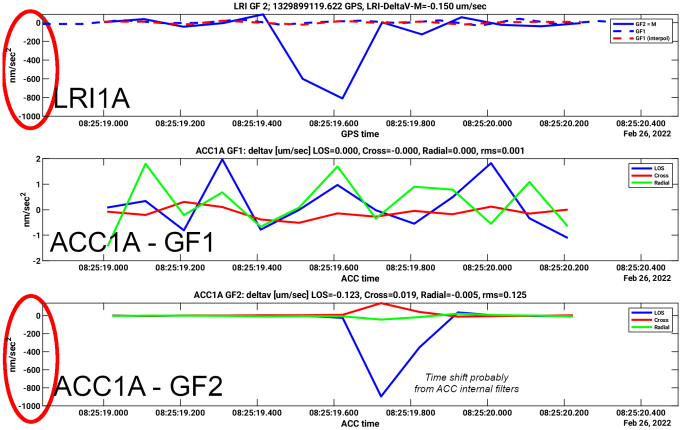
- The sensitivity of the LRI is limited by Laser frequency noise at the highest frequencies and Tilt-To-Length coupling (TTL) below. Both are well below the requirement
- The TTL can be measured during center-of-mass calibration maneuvers and can, in principle, be subtracted
- Due to the low noise, some fine structures of the gravity field can be explored, that can not be resolved with the KBR (see Ghobadi-Far et al. [2])
- The sensitivity of the LRI allows observation of non-grav. linear accelerations (line-of-sight)
- Further, the LRI helps characterizing the spacecraft platform in terms of vibration measurements of thruster valves or resolving non-gravitational linear accelerations

- The LRI phase exhibits undesired phase jumps (PJ) on thruster activation, caused by mechanical vibrations, that induce fast frequency variations in the laser crystal (see figure)
- A **low-pass filtered and decimated** version of these vibrations is visible in LRI1A, magnitude mostly below 1 µm
- **For LRI1B, a PJ-removal algorithm removes most of the signature using a template-based approach for detection, modeling and subtraction**
- See Laura Müller's presentation (EGU22-6109, today 9:30)



Thruster-shock induced PJ in diagnostic (high-rate) data

LRI Measurements
Momentum Transfer Events (MTE)

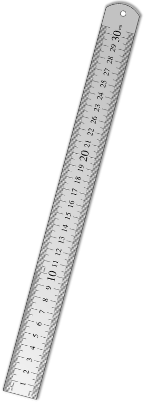


- At some instances, LRI and ACC measure similar peaks in the line-of-sight acceleration
- Event rate $\approx 35\,/\text{year}/\text{SC}$
- Likely caused by Micro-Meteorites impinging the satellite body
- Here, the LRI helps disentangling gravitational signal from non-gravs and noise / measurement errors

LRI Measurements

Scale Factor Estimation: The Ruler

- The conversion factor from LRI measured phase to a range in meter is given by the resonance frequency of the **optical cavity ν, which is very stable** [12]
- However, the **absolute value of the frequency is only known roughly** and scale is determined on a daily basis by fitting LRI phase to KBR range
  $\Rightarrow$ Scale might be falsified by errors in LRI and KBR [5]

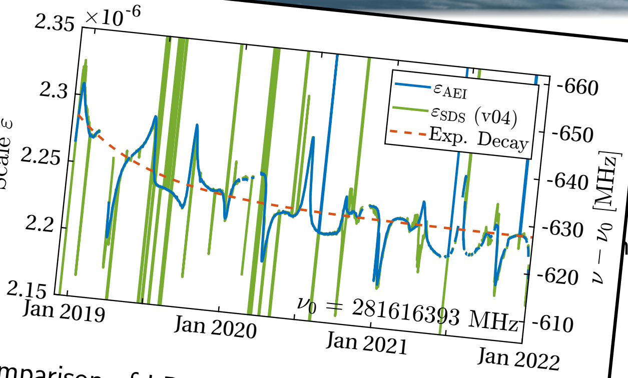


LRI Measurements

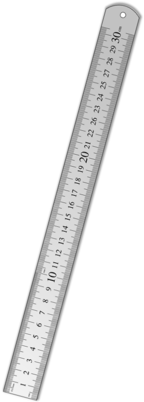
Scale Factor Estima… The Ruler

- The convers… …er is given by the … …is **very stable**…
- However, t… **roughly** a… …ase to KBR ra…

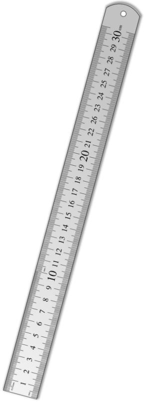
  ⇒ Scale n…



Comparison of LRI and KBR reveals 10^{-7} variations in scale factor (watch out for paper in preparation)



- The conversion factor from LRI measured phase to a range in meter is given by the resonance frequency of the **optical cavity ν, which is very stable** [12]
- However, the **absolute value of the frequency is only known roughly** and scale is determined on a daily basis by fitting LRI phase to KBR range
  $\Rightarrow$ Scale might be falsified by errors in LRI and KBR [5]
  $\Rightarrow$ Not possible without microwave ranging!
  $\Rightarrow$ For future missions: an absolute frequency reference, or **Scale Factor Unit (SFU)**, is needed. Further reading: [9], [10]



Recent/Planned LRI Activites

Recent:

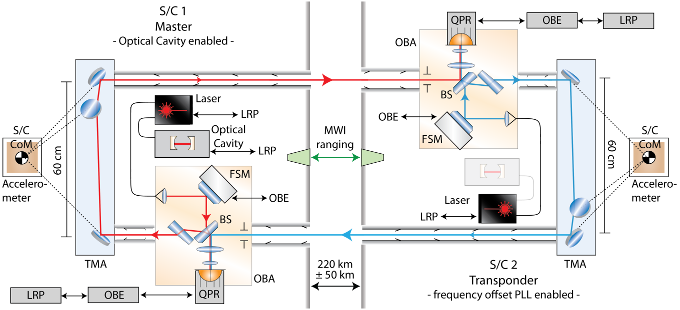
- NADIR-pointing periods for analyzing ACC performance, LRI was off on these days (approx. 2 days per week from May-2021 until Feb-2022)
- Role Swap (Feb-23, 2022), switch reference/transponder role. GF-2 is now reference (as it was from launch until 12th December 2018).

Planned:

- JPL LRI team prepares update of LRP flight software to mitigate effect of phase jumps in-flight

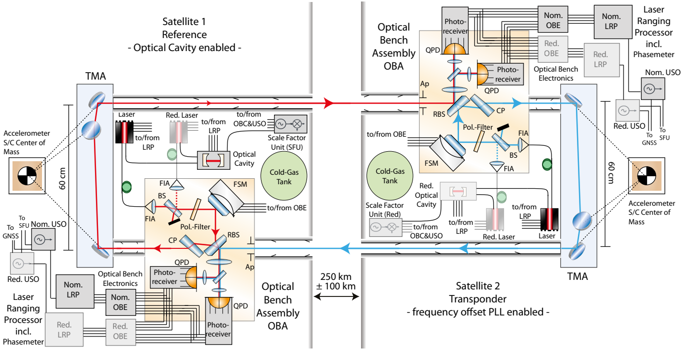
Concept Design: LTI for NGGM/MCM/GRACE-I

- Future missions in planning are the US-German Mass-Change-Mission (MCM) / GRACE-Icarus (launch ≈2027) and the ESA-lead NGGM / MAGIC (planned ≈2030s)
- Developed by the same team as the LRI consisting of: + partners



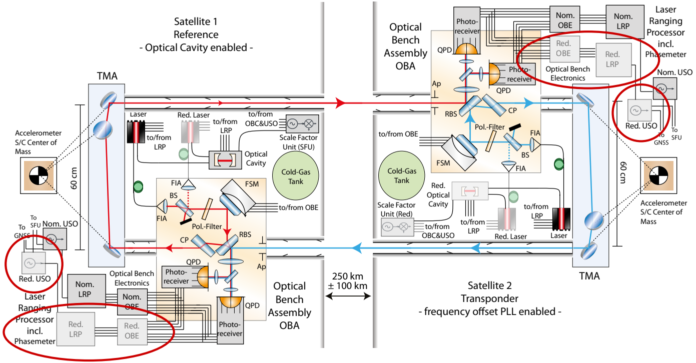
- Future LRI-like instruments use the heritage layout (shown left)
- Ranging noise level expected to be **similar to GFO-LRI**, sufficient for gravity field maps
- Advance design with lessons learned, improve redundancy

Concept Design: LTI for NGGM/MCM/GRACE-I



Currently in (pre-) Phase A. All information on following slides is preliminary and might change.

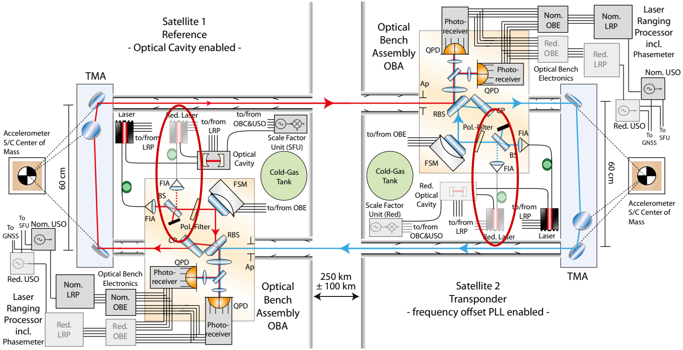
Concept Design: LTI for NGGM/MCM/GRACE-I



Redundant Electronics:

- Hot-redundant Photoreceivers (as LRI)
- Cold-redundant OBE, LRP and USO on both sides
- USO now belongs to LRI, not MWI

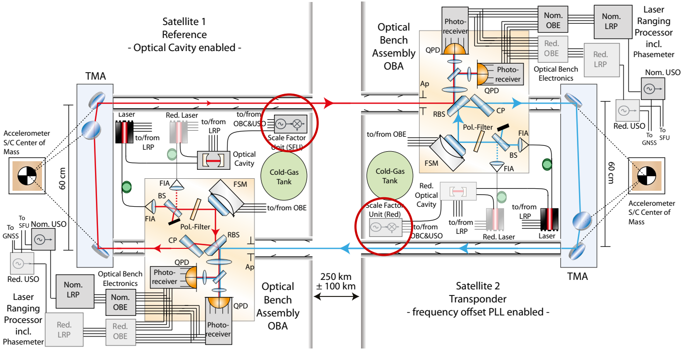
Concept Design: LTI for NGGM/MCM/GRACE-I



Redundant Lasers:

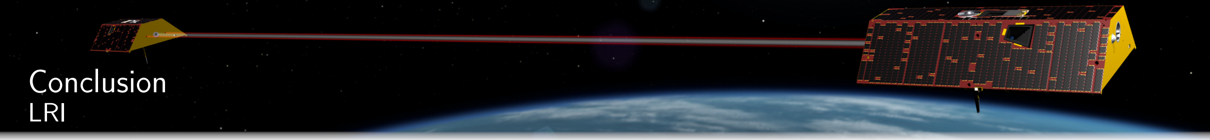
- Two lasers on both sides
- Additional fiber injector and beam combiner needed (no mechanical fiber switching)

Concept Design: LTI for NGGM/MCM/GRACE-I



New Scale Factor Unit (SFU):

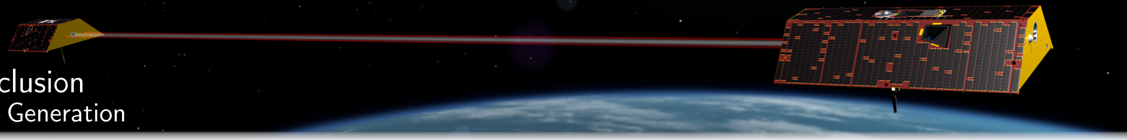
- Measurement of the absolute laser frequency ν (conversion factor from phase to range)
- Redundancy concept as for the optical cavity: One on each SC



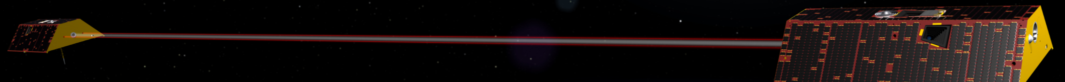
Conclusion
LRI

- **The LRI performs well after four years in orbit**
- LRI-derived range has less noise, and thus higher SNR compared to KBR
  - Reveals weaker feature of the gravity field
- Phase Jumps are well understood and removed in LRI1B
  - will be mitigated in-flight by software update
- LRI measures similar acceleration peaks as ACC $\rightarrow$ Micro-Meteorites

Conclusion
Next Generation



- Future missions are being studied in (pre-) phase-A activities: MCM/GRACE-I mission is planned to launch ≈2027, ESAs NGGM/MAGIC is planned for ≈2030s
- The next generation LRI might be developed by the same team (AEI, STI, JPL/NASA)
- Goal sensitivity is slightly better than LRI requirement
- **Evolve LRI** from technology demonstrator to main instrument with appropriate redundancy, include lessons learned
- Future missions might have an **additional unit for determination of the "ruler"**, i. e., the absolute laser frequency



Contact Information

Questions?

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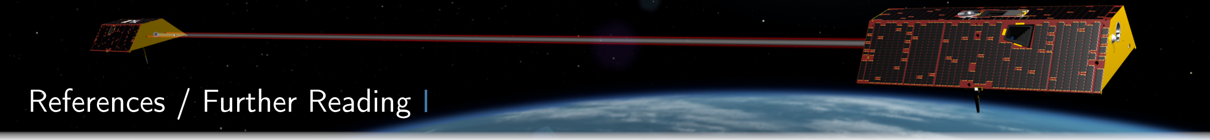

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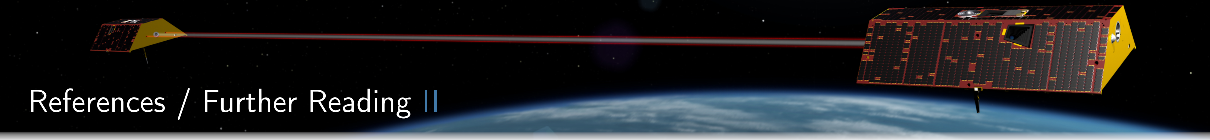

References / Further Reading II

[11] 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.

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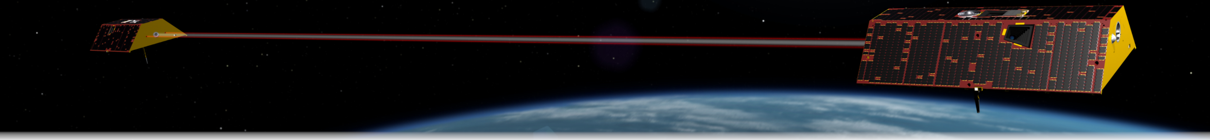
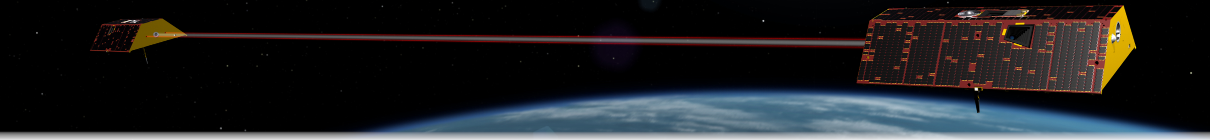
Unsorted Appendix

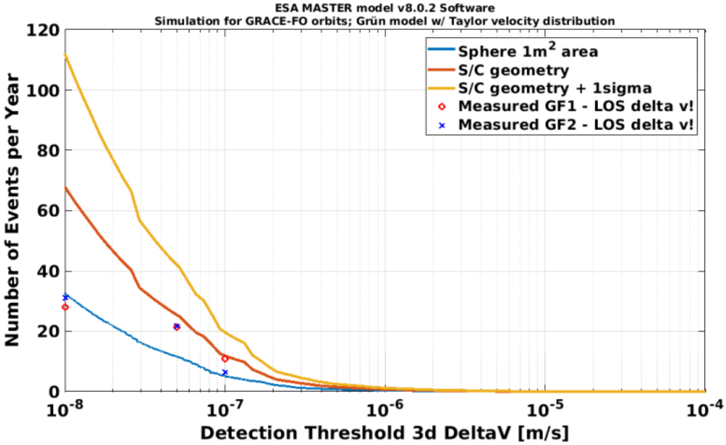


LRI Working Principle

- The LRI is built in a “racetrack” configuration, since the line of sight between the two GFO spacecraft is blocked by cold-gas tanks and MWI antennas. A triple-mirror assembly (TMA) routes the beam around those.
- The TMA’s properties ensure parallelity of the incoming and outgoiing beam, and the TMA vertex (intersection point of mirror planes) is the LRI reference point.



Momentum Transfer Events (MTE)



Measured data (crosses, circles) match the predictions from particle density models. Deviation at $1 \times 10^{-8}\,\mathrm{m\,s^{-1}}$ since MTE's can not be detected well in LRI data at these low Δv values.