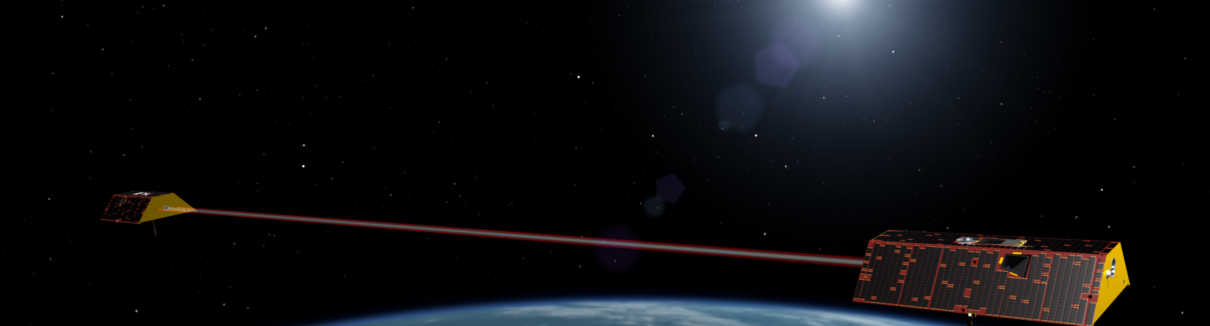

Alternative Level 1A to 1B Processing of GRACE Follow-On LRI data

Malte Misfeldt, Vitali Müller, Gerhard Heinzel and Karsten Danzmann

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

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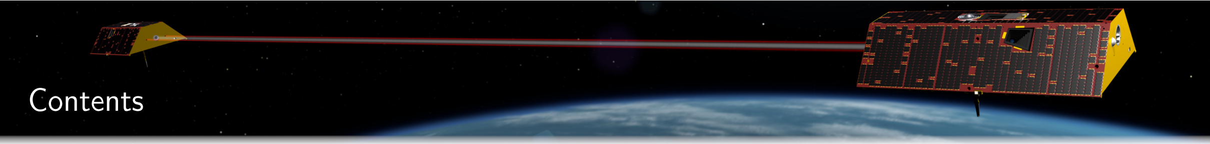

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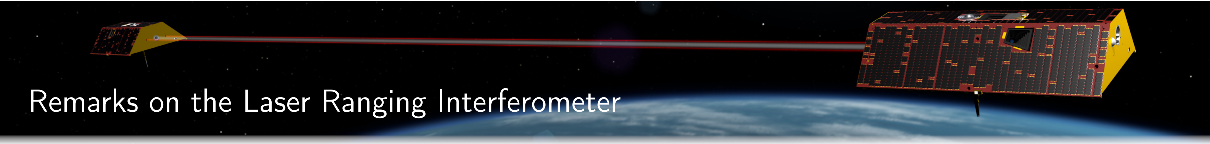


Remarks on the Laser Ranging Interferometer

The Laser Ranging Interferometer (LRI) onboard the GRACE-FO mission successfully demonstrated the **feasibility of inter-satellite laser ranging** [1].

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

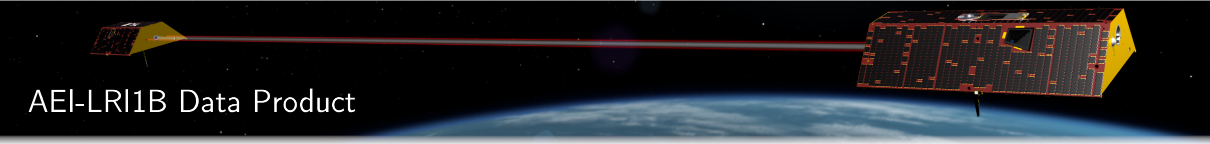
Long uninterrupted measurements, e.g. for more than 106 days, which is approximately 1650 orbital revolutions.

The LRI team at the AEI Hannover is **analyzing the LRI data** in detail and **developing processing algorithms**.

AEI-LRI1B Data Product

Overview

- We derived an **AEI-LRI1B data product**, for which we use the raw Level-0 spacecraft telemetry alongside the official SDS v04 releases of timing products (CLK1B, TIM1B) and navigation solutions (GNI1B).
- **Major enhancements** over v04-LRI1B are:
  1. Advanced template-based deglitching (see below and [1, 3])
  2. Calibrated model for the scale factor (see below)
  3. A numerically more accurate Light Time Correction (LTC) (see [4])
  4. Enhanced CNR accuracy: reversing the scalloping loss and accounting for frequency-dependent photo receiver noise (see [3])
- Our AEI-LRI1B data set for the month of January 2019 is available at https://wolke7.aei.mpg.de/s/xDL3pmeSD65dqT4 or via the QR-Code:



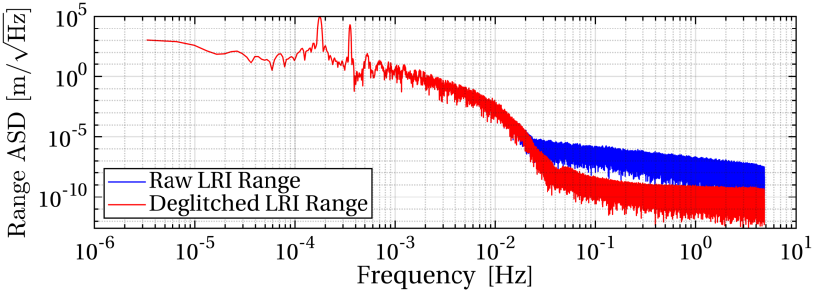
AEI-LRI1B Data Product

In the next slides, we discuss the following aspects of our AEI-LRI1B data product:

- Phase Jumps
- Phase Conversion
- Scale Factor Estimation
- Comparison of AEI-LRI1B vs. v04-LRI1B

The LRI phase shows jumps, which are correlated to attitude thruster activation [1].

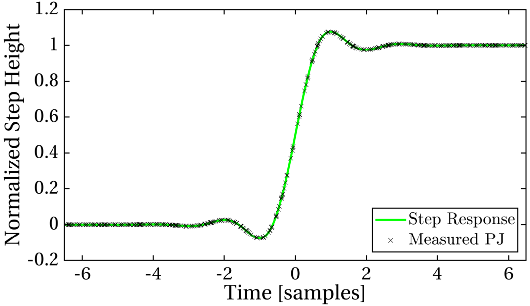
- Working hypothesis: the thruster's valve causes vibrations on opening and closure which rapidly deforms the laser crystal. This mechanical stress changes the refractive index of the crystal and hence the laser's frequency.
- Phase jump removal (or "deglitching") required to get low-noise phase data.



Phase Jumps

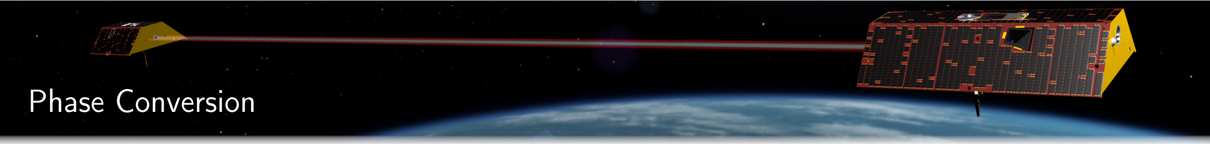
How are they removed?

- Since the step response of the LRI internal decimation filter is known, the steps can be removed in post-processing.
- We only need to fit two parameters: The amplitude and the exact timing w.r.t. the sampling rate



We use the above template to model all jumps from both, transponder phase φ_T and master phase φ_M. Afterwards, we can subtract the cleaned time series from each other. To do so, we need to interpolate the transponder measurements to the master time.

$$\varphi_{\mathrm{LRI}}(t_M) = (\varphi_T(t_T(t_M)) - \varphi_{\mathrm{model},T}(t_T(t_M))) - (\varphi_M(t_M) - \varphi_{\mathrm{model},M}(t_M)) \qquad (1)$$



Phase Conversion

We now derive the LRI range as the integral over the range rate

$$\dot{\rho}_{\mathrm{LRI}}(t) = \underbrace{\frac{c}{\nu(t)}}_{\text{scale}} \cdot \underbrace{\left.\frac{\mathrm{d}\varphi_{\mathrm{LRI}}(\tau)}{\mathrm{d}\tau}\right|_{\tau=t}}_{\text{phase rate}} \qquad \text{Range Rate} \qquad (2)$$

$$\rho_{\mathrm{LRI}}(t) = \int_{t} \dot{\rho}_{\mathrm{LRI}}(t')\ \mathrm{d}t' + \mathrm{const.} \qquad \text{Biased Range} \qquad (3)$$

Here, c denotes the speed of light in vacuum.

- Switching to the range rate domain is necessary, as we do consider variations of the scale factor $\nu(t)$.

The derivation of the scale factor is shown in the next slides.

Scale Factor Estimation

To convert the phase measurements to an equivalent range, the laser's frequency ν is needed, cf. eq. (2). ν varies over time and can be derived in two ways:

1. Cross-calibrate the LRI range with the MWI range once per day (used by SDS for v04-LRI1B)
2. Use a physical model based on on-ground measurements and empirical parameters (preferred by AEI Hannover)

We split our model in two parts

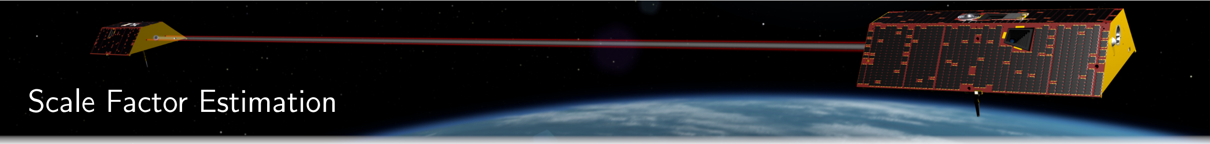
$$\nu(t) = \underbrace{\nu_{\text{ground}}(t)}_{\text{uses LRI telemetry}} + \underbrace{\nu_{\text{empirical}}(t)}_{\substack{\text{uses empirical parameters from} \\ \text{cross calibration with MWI}}} , \tag{4}$$

where ν_{ground} contains short term variations and $\nu_{\text{empirical}}$ compensates long term drifts, e.g. through aging processes. The drift is in the order of $1\,\mathrm{Hz\,s^{-1}}$.

Scale Factor Estimation

- For the first term of eq. (4), we use the laser telemetry (e.g. from LHK data product) and the laser temperature (HRT, not yet available in v04) to estimate the absolute laser frequency

$$\nu_{\text{ground}}(t) = \underbrace{\begin{pmatrix} c_{\texttt{pztIL}} \\ c_{\texttt{pztOOL}} \\ c_{\texttt{thermIL}} \\ c_{\texttt{thermOOL}} \\ c_{\text{TRP}} \end{pmatrix}}_{\text{Coupling constants}} \cdot \underbrace{\begin{pmatrix} \texttt{pztIL}(t) \\ \texttt{pztOOL}(t) \\ \texttt{thermIL}(t) \\ \texttt{thermOOL}(t) \\ \texttt{lasTRP}(t-\tau) - T_{\text{ref}} \end{pmatrix}}_{\text{Laser telemetry}} + \underbrace{\nu_0}_{\text{const.}} \tag{5}$$



Scale Factor Estimation

Exemplary values for GF-1 (preliminary):

$c_{\texttt{pztIL}}$	$c_{\texttt{pztOOL}}$	$c_{\texttt{thermalIL}}$	$c_{\texttt{thermalOOL}}$	c_{TRP}	ν_0
10 MHz	90 MHz	1.0380 GHz	8.9921 GHz	$-8.454\,\mathrm{MHz\,K^{-1}}$	281 614 752 MHz

The on-ground measurements are not very sensitive to the PZT coupling, hence the design values are displayed.

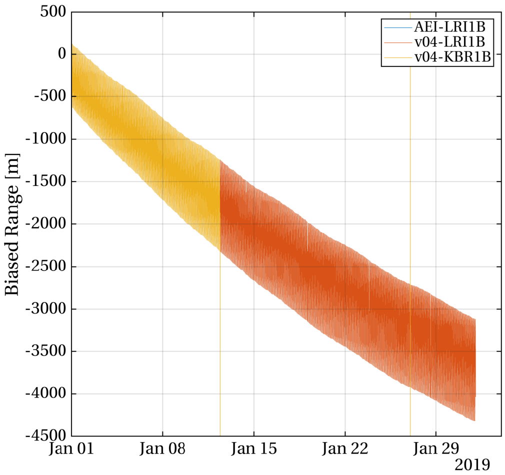
Advantages:

- Telemetry-based modeling may allow to resolve sub-daily variations
- We have a model that is continuous in time and not a daily constant, hence it has no discontinuities at day-bounds
- Our derivation of the scale is independent from the MWI on daily or weekly scales, however we remove long term trends by scaling to MWI measurements.

Comparison of AEI-LRI1B vs. v04-LRI1B

LRI Range

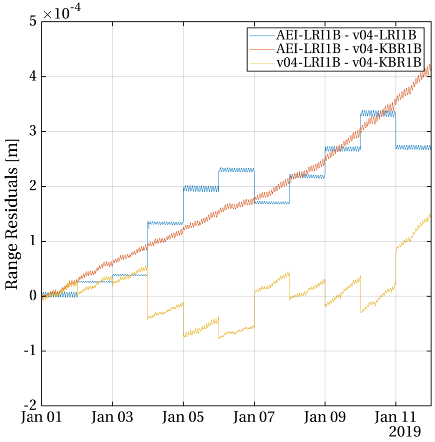
- On large scales, the biased range as measured from LRI (AEI and SDS data) agree well with the KBR
- The microwave IPU rebooted on Jan. 12 and Jan. 26, resulting in a new bias, which is not subtracted here



Comparison of AEI-LRI1B vs. v04-LRI1B

LRI Range Residuals

- This comparison already includes the Light Time Correction (LTC)
- The AEI-LRI data is continuous, while the v04-LRI uses a daily parameter-estimation strategy to derive the scale factor and time offset of the LRI w.r.t. MWI range.
- We observe a drift $< 0.5\,\text{mm}$ per week of our AEI-LRI1B w.r.t. the two v04 data sets, which is not yet fully understood

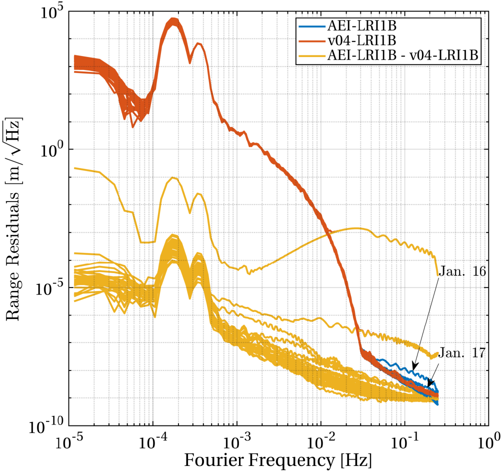


Comparison of AEI-LRI1B vs. v04-LRI1B

LRI Range in Spectral Domain

Here, spectra are computed for every day in Jan 2019

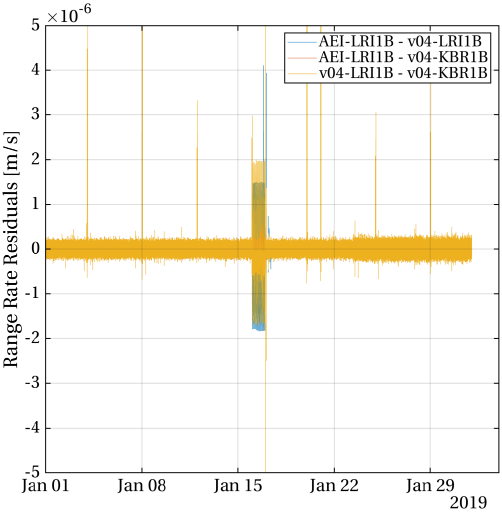
- In high frequencies, the overall difference of AEI-LRI1B and v04-LRI1B is in the order of $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$
- Jan 16 and Jan 17 exhibit large phase jumps, that are not removed properly in v04-LRI1B.
- We observe differences in the 1/rev and 2/rev tones, which originate from the different scale and time-offset parameters



Comparison of AEI-LRI1B vs. v04-LRI1B

LRI Range Rate Residuals

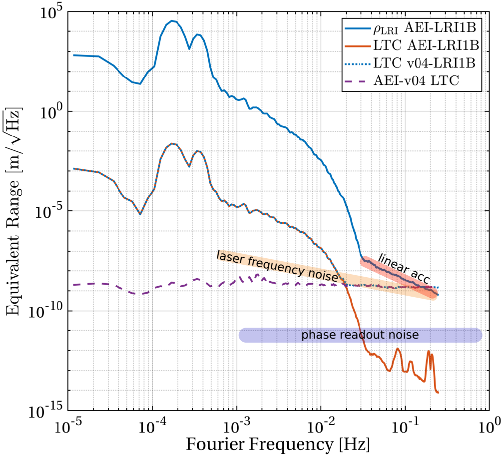
- The range rate difference is in the order of $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$
- Jan 16 shows large 1/rev and 2/rev oscillations. Here, a very large phase jump was not removed properly in v04-LRI1B and prevents a correct scale and time-offset estimation
- The large spikes at day bounds are discontinuities in the v04-LRI1B LTC data.
- The smaller spikes originate from residual phase jumps in the v04-LRI1B data.



Comparison of AEI-LRI1B vs. v04-LRI1B

LRI Light Time Correction in Spectral Domain

- AEI-LRI1B uses an analytical formalism to compute the Light Time Correction (LTC) [4], while the v04-LRI1B uses a numerical method.
- Towards high frequencies, the v04 LTC introduces numerical noise, that is higher than the LRI measurements (indicated as colored bars in $m/\sqrt{Hz}$-domain)
- The AEI-LTC computation improves the LRI signal at frequencies > 20 mHz

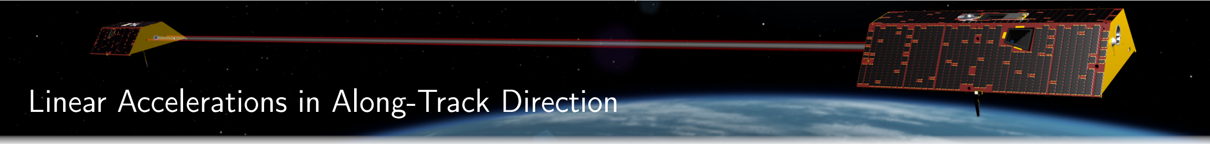


Comparison of AEI-LRI1B vs. v04-LRI1B

Changes to the File Header

We changed some information in the YAML header of our AEI-LRI1B.

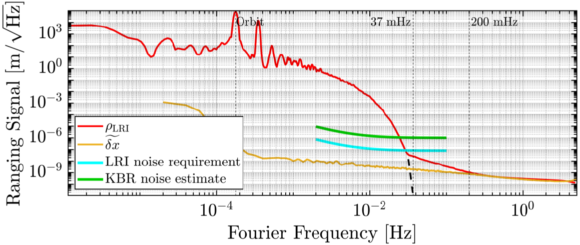
- `iono_corr` describes the applied scale factor in units of meter. It is derived from laser telemetry (see above) and already applied to the `biased_range` entry.
- `K_A_SNR` indicates the Carrier-to-Noise ratio. This is an integer number in v04-LRI1B, however we use a floating point number.
- `Ka_A_SNR` is a time offset, which is fixed to 50 µs. This field is not used by v04-LRI1B, however a time offset is estimated as well
- `qualflg`: We use the bits 1 and 2 to indicate phase jumps (bit 1 = Phase Jump removed, bit 2 = Phase Jump was large, some residuals may still be present). v04-LRI1B does not use bit 1 or 2.



Linear Accelerations in Along-Track Direction

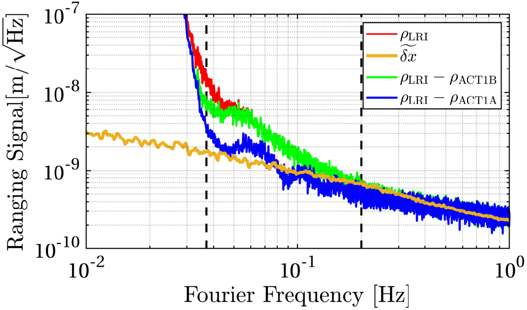
The spectral density of the LRI ranging signal ρ_{LRI} shows three main regions

1. $f < 37\,\mathrm{mHz}$: Here, the gravitational effects, i.e. the static gravity field, dominate the ranging measurement
2. $f \geq 200\,\mathrm{mHz}$: The LRI range measurement is dominated by instrument noise, i.e. laser frequency noise (LFN), as expected by [2]
3. $37\,\mathrm{mHz} \leq f < 200\,\mathrm{mHz}$: Neither the gravity signal nor LFN is dominating. See next slides



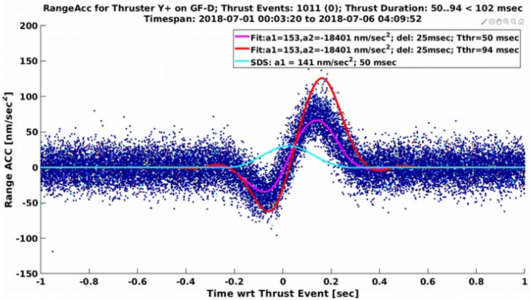
Linear Accelerations in Along-Track Direction

- The spectral density of the LRI ranging signal ρ_{LRI} shows an unexpected elevation between 37 mHz and 200 mHz.
- This elevation was traced back to dominating non-gravitational linear accelerations. We can subtract parts of this signal by calculating the displacement ρ_{ACT1A} (in along-track direction) using the ACT1A data product [3].



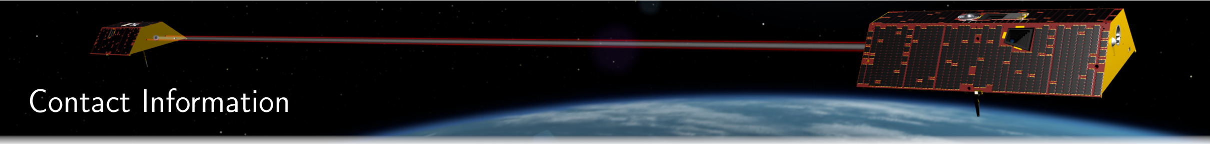
Linear Accelerations in Along-Track Direction

- This "bump" frequency range is usually not addressed during gravity field recovery, since the highly filtered ACT1B is used rather than ACT1A.
- The low noise of the LRI allows diagnostics across other instruments onboard the satellites, e.g. thruster-response modeling (at least in along-track direction) for refining the ACT data product, as indicated by the figure below.



Conclusion

- We presented a few insights into the LRI data analysis at the AEI Hannover
- We derived an **AEI-LRI1B data product**, which implements the afore mentioned improved algorithms. The data is publicly available: (https://wolke7.aei.mpg.de/s/xDL3pmeSD65dqT4 or via the QR-Code) Feel free to use it and give feedback!
- A brief overview on **phase jumps and removal strategies** is given
- Two strategies of **scale factor estimation** are presented, of which our preferred one is to large extend independent from the MWI
- We observed **dominating non-gravitational linear accelerations** in the LRI data at frequencies from 37 mHz to 200 mHz, which opens possibilities for **diagnostics among other instruments**



Contact Information

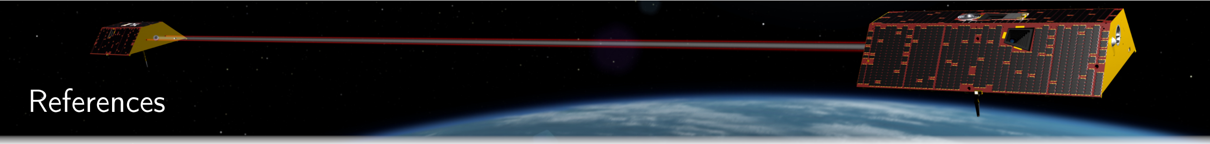
Feel free to ask questions!

Malte Misfeldt
for the LRI team

malte.misfeldt@aei.mpg.de

Max-Planck Institute for Gravitational Physics
(Albert Einstein Institute AEI)

Hannover - Germany



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[3] Malte Misfeldt. “Data Processing and Investigations for the GRACE Follow-On Laser Ranging Interferometer”. MA thesis. Institute for Gravitational Physics, Leibniz Universität Hannover, June 2019, p. 121. DOI: https://doi.org/10.15488/9639.

[4] Vitali Müller. “Design Considerations for Future Geodesy Missions and for Space Laser Interferometry”. PhD thesis. Leibniz Universität Hannover, July 2017.