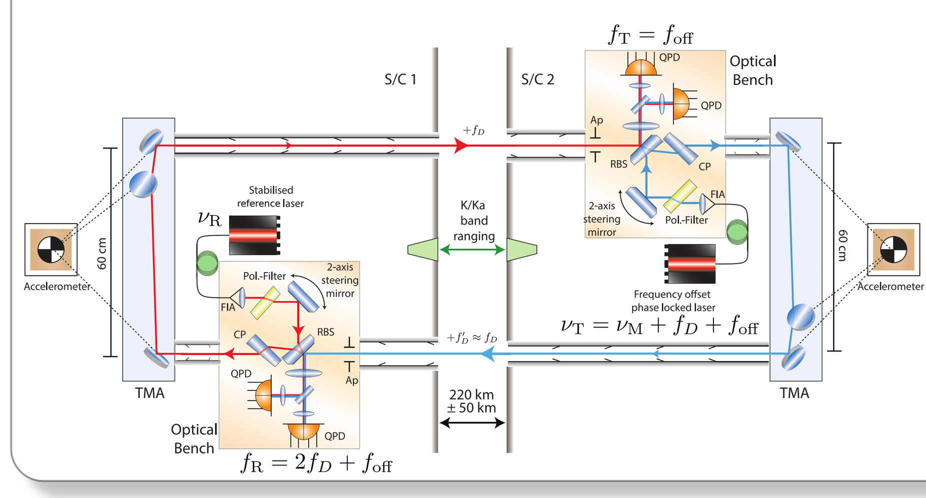
Albert Einstein Institut
Institut für Gravitationsphysik
Leibniz Universität Hannover

Radiation Effects and other Features in the Laser Ranging Interferometer Data

Malte Misfeldt, Pallavi Bekal, Laura Müller, Vitali Müller and Gerhard Heinzel

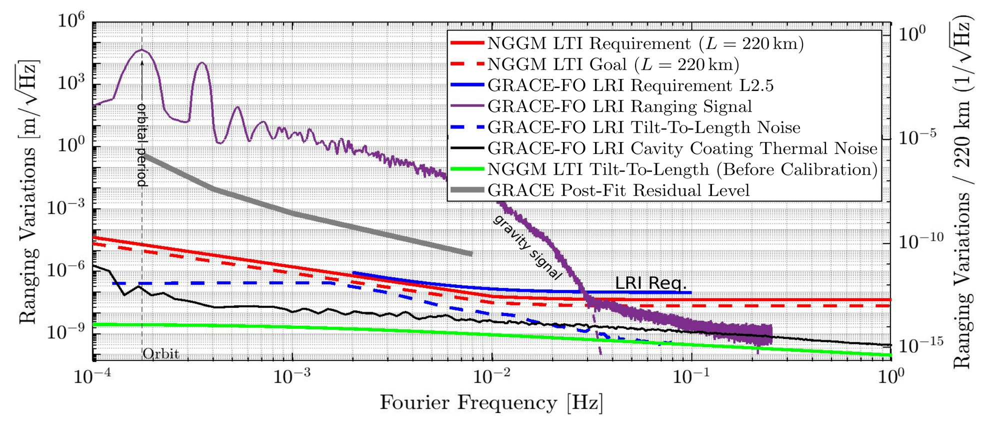
Max-Planck Institute for Gravitational Physics, Hannover
Institut für Gravitationsphysik, Leibniz Universität Hannover

The **Laser Ranging Interferometer (LRI)** on GRACE Follow-On is a technology demonstrator that allows to resolve short-term **inter-spacecraft distance variations** of atomic size over a 220 km baseline [1]. It was put into operation on 14th of June 2018 and provides low-noise data since then.
Many of the LRI **technologies demonstrated** on GRACE-FO, like weak light interference, phase-tracking of MHz beatnotes, frequency-offset phase locking, will also be used in the **space-based GW observatory LISA**.
GRACE-FO is based on a partnership between JPL and GFZ, the LRI instrument has been developed in a US/German collaboration [1].



LRI Setup. The laser beam of the stabilized master laser is aligned to the incoming beam via the Fast Steering Mirror (FSM) control loop using Differential Wavefront Sensing (DWS). The Triple Mirror Assembly (TMA) routes the beam to the distant transponder S/C. On the transponder side, the laser frequency is offset-frequency locked to the incoming beam, again aligned and routed back. The beatnote frequency on the master side is the sum of the transponder offset frequency (10 MHz) and Doppler shifts (i.e. the gravity signal).

Measurement Performance of the LRI

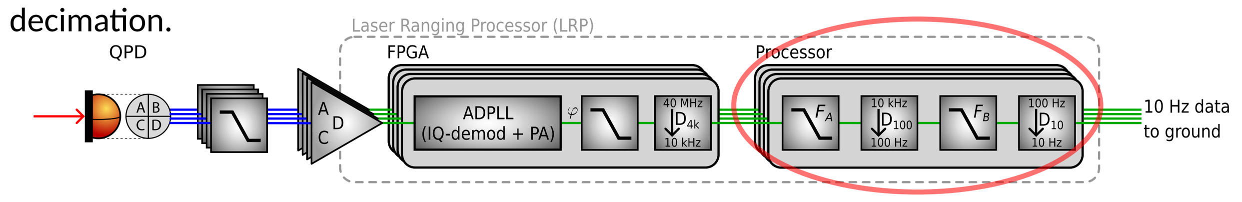


Linear Spectral Density of a typical LRI ranging measurement. The orbital period peak is at 0.17 mHz, Earth static gravity signal above. From 200 mHz on, the LRI noise dominates the measurement.

The ranging performance of the LRI is 200 pm/√Hz at 5 Hz [1], well **below the requirement** even for next generations of gravimetric missions [4]. The dominant noise sources are the cavity coating thermal noise (black line) and so-called tilt-to-length (TTL) coupling from spacecraft rotations (blue dashed, [6]). The ranging signal in the frequency band from 30 to 200 mHz is dominated by **non-gravitational accelerations** like atmospheric drag and thruster activations [5].

Single-Event Upsets: Errors caused by Radiation

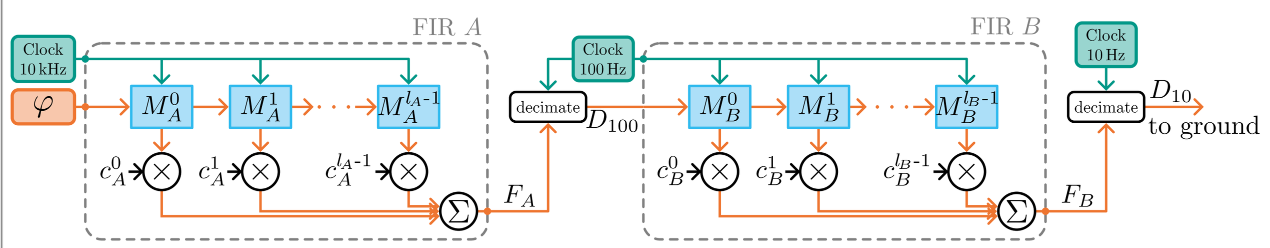
The electronics onboard every spacecraft is **prone to SEUs** due to the **hazardous radiative environment in space**. These SEUs can manifest as bitflips within memory cells of the LRI processor (LRP), where the bitflip might occur **within the digital filtering** and decimation.



A bitflip manifests as an **instantaneous and non-persistant peak** in the measurement. Its shape in the decimated 10 Hz data is determined by the coefficients of the two FIR decimation filters F_A and F_B. This analysis is available as preprint in [2].

Digital FIR Filters within the LRP

The two digital FIR filters within the LRP processor comprise a few hundred registers each, with $l_A > l_B$. Each register M^i has a corresponding filter coefficient c^i. The measurement data passes the registers, which are implemented as a cyclic ring buffer. After the filter, decimation (sample picking) takes place.

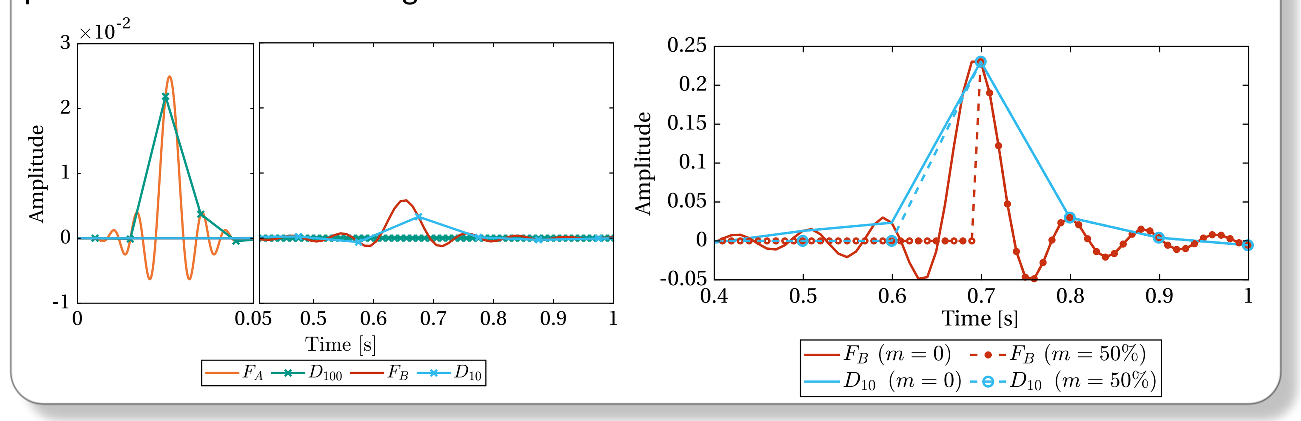


A bitflip in any of the registers will spoil the data sent to ground. However, as FIR filters are deterministic, the error can be identified, modelled and subtracted.

Topic: Single Event Upsets

Simulation of Single Event Upsets

In a simulation environment, parts of the LRP were implemented to mimic the influence of an SEU and to **identify the free parameters**, which are the occurrence time (w.r.t. the sampling rate), the affected register number *m* (each filter feature a few hundred registers and corresponding filter coefficients), and the magnitude (the bit-number of the 64-bit register). Depending on the register number, the 10 Hz output data might look cropped. The simulation provides **templates, stored in look-up tables**, for detection and parameter-estimation on flight-data.



Detection & Parameter Estimation

SEUs candidates are identified as peaks in the first derivative of the measured phase data, although the analysis is performed in phase domain. They can easily be distinguished from phase jumps (see the topic at top right), as they only occur in one of the four phase channels. Furthermore, an SEU produces a short-lived peak, not a persistent step. Once detected, a short segment of data is extracted from the measured phase and, based on the simulated LUTs, the parameters of each event are determined employing the **maximum likelihood method.**

$$\mathcal{L}(\varphi|\vartheta) = \frac{1}{\sqrt{|2\pi\Sigma|}} \exp\left(-\frac{1}{2} r(\vartheta)^{\mathsf{T}} \cdot \Sigma^{-1} \cdot r(\vartheta)\right)$$

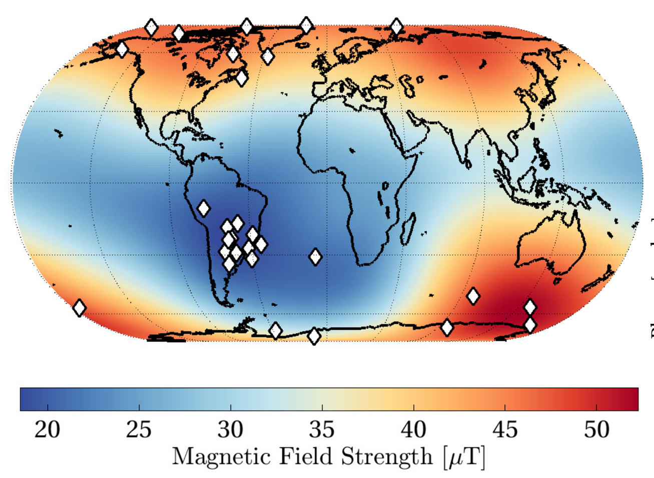
Likelihood of ϑ, given the data φ; observed data; parameter estimates; covariance matrix; residuals: $r(\vartheta) = \varphi - a \cdot \mathrm{LUT} - \mathrm{poly2}$

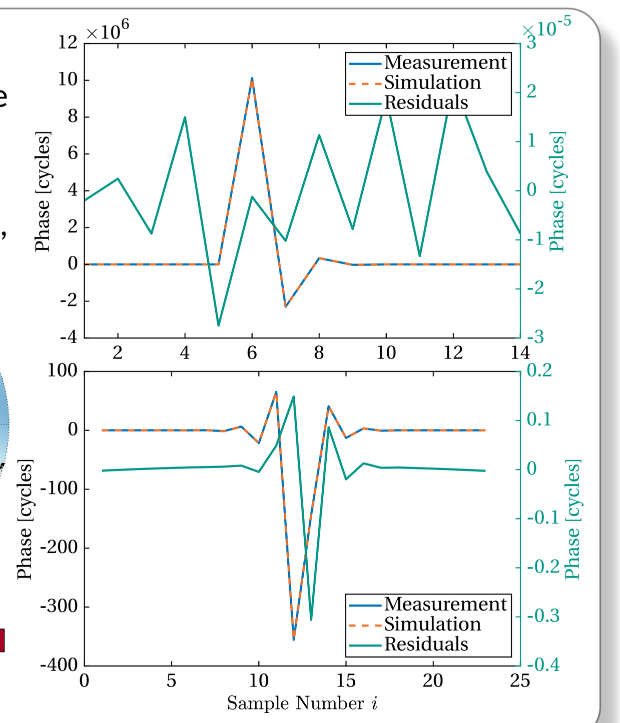
The parameters ϑ comprise of the scale a and the polynomial coefficients.

In a first step, the parameters ϑ for all LUT entries are computed, before the global maximum in likelihood over the two LUTs for filters A and B is selected. The covariance matrix Σ is computed numerically from the measurement noise in absence of an SEU event.

SEUs: Results and Discussion

- In total, **29 events** were detected in 2018-2022. They are **evenly distributed** among GF-1 and GF-2 and also over the four data channels. See [2] for the full analysis of all events.
- Filter A shows more events than filter B (19 vs. 10), which is expected as filter A has more registers and thus a physically larger area to be hit.
- Most of them cluster within the **South-Atlantic Anomaly**, where the Earth magnetic field is weakest and thus provides less shielding effect, e.g., against solar radiation (left figure).
- After removing the SEU model from data, **almost no residuals** can be seen (top right figure).
- In some cases, the retrieved scale α of the LUT template does not correspond to integer bit numbers: In these cases, **more than one memory cell was affected** by a single particle.
- Other rare cases show a second SEU-like trace in the residuals, which could be caused by two almost simultaneous events separated by a small time-delay (bottom right figure).
- As bitflips are very rare, short-lived, and non-persistent events, their removal or non-removal is expected to have **low impact on gravity field recovery** as many processing centers amploy outlier detection.
- With the presented algorithm, we correct SEUs in our LRI Level1B data products (see [X]). Future missions might mitigate the effect by employing error-correction techniques in hardware.

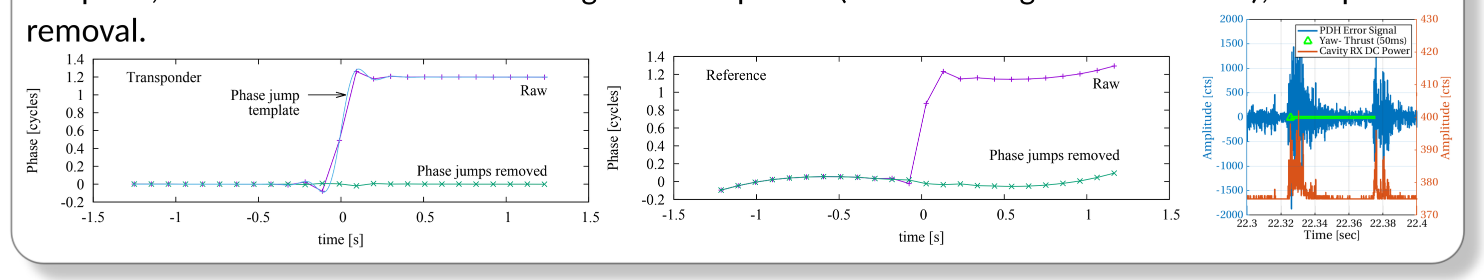




Topic: Phase Jumps

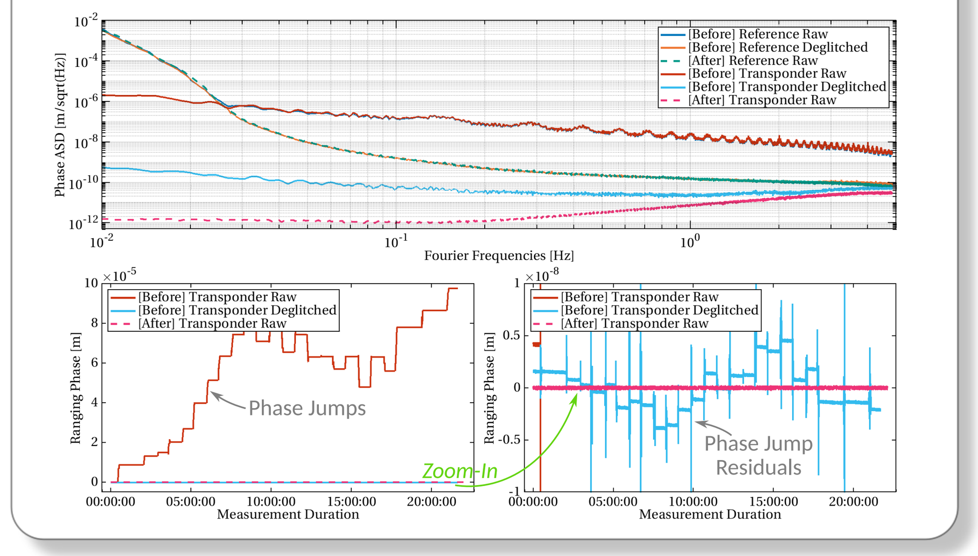
Phase Jumps: Micro-Shock induced Laser Frequency Changes

Early in the mission, **spurious steps in the measured LRI phase** were found [1]. They can be explained by **vibration of the NPRO laser crystal**, causing mechanical stress and thus changing the refractive index of the crystal. The vibrations originate from activation of attitude control thrusters and propagate through the spacecraft platform. As they are an actual property of the light travelling between the spacecraft, the phase jumps are measurable on both, reference and transponder, with the same magnitude, separated by the light-travel-time.
A so-called **deglitching algorithm** was initially used to subtract the jumps in post-processing. It used a template, derived from the antialiasing filter response (see box "Digital FIR Filters"), for precise removal.



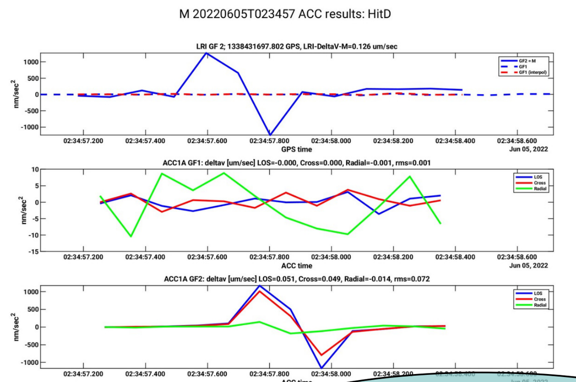
Flight Software Update

Meanwhile, an update of the FPGA software of the LRI instrument was performed to suppress the jumps in-flight by adjusting the phaselocker control loop on the transponder. Now, the raw measurements directly show the cavity frequency noise on reference, and electronic readout noise on transponder side.



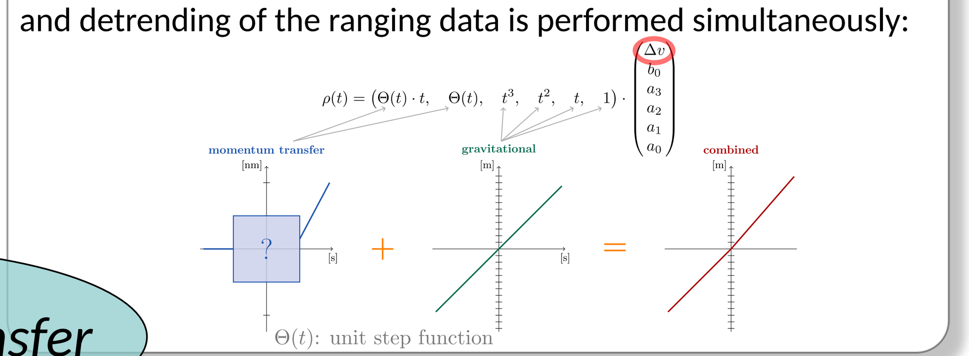
Momentum Transfer Events: Micrometeorites?

LRI and accelerometer are both **sensitive to accelerations in along-track** (or line-of-sight) direction. This allows inter-comparison, despite the degraded ACC performance on GF-2. There exist a few events per month, in which **LRI and ACC measure similar peaks in the line-of-sight acceleration** (blue curves). The figure shows an event occuring in the LRI (top panel) as well as in two axes of the ACC on GF-2 (bottom panel), while no excitation is recorded on GF-1 (center panel).
Unfortunately, ACC and LRI do not use the same antialiasing and decimation filters, hence their traces can not be compared directly and their results do not match perfectly.
The figure shows a **good example for such an event**, with high consensus among LRI and ACC.



Δv Estimation

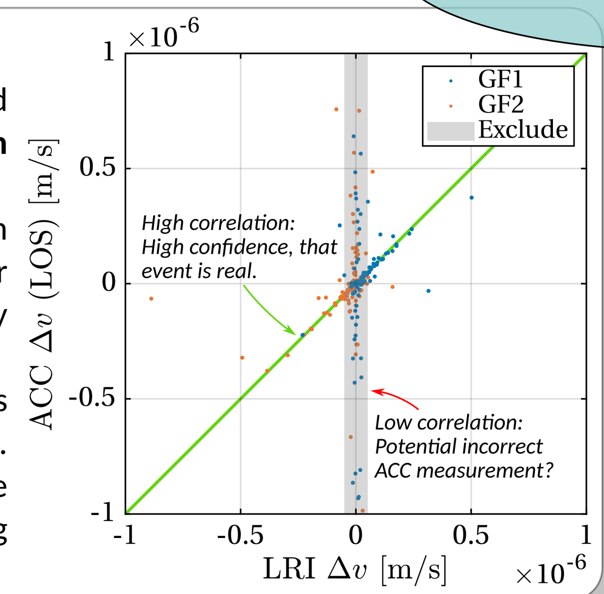
For deriving the Δv of a possible MTE event, parameter estimation and detrending of the ranging data is performed simultaneously:



Topic: Momentum Transfer Events

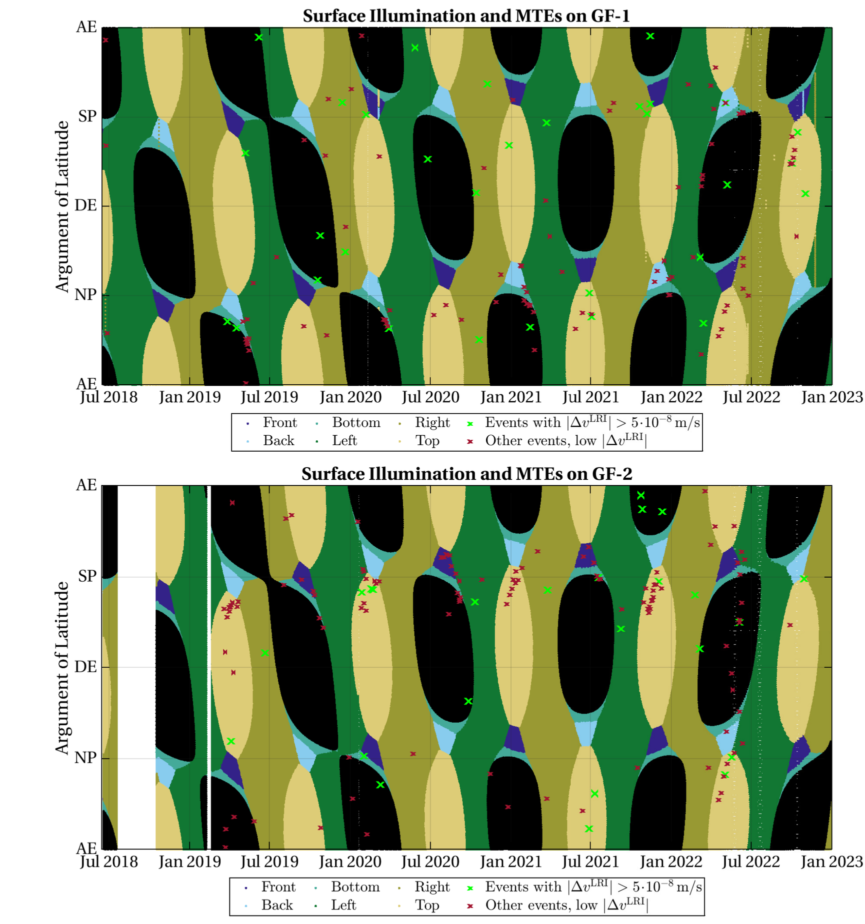
Δv: ACC vs LRI

The comparison of Δv estimates from ACC and LRI shows some events with **high correlation** (indicated by the green line).
We assume that events with low correlation between LRI and ACC Δv are vibrations or shocks on the spacecraft that are incorrectly resolved by the ACC.
Events with $\Delta v < 8 \cdot 10^{-5}\,\mathrm{m/s}$ are regarded as sensitivity level of the LRI at the current stage. The clustering of GF-1 - related events at the negative side is expected, as GF-1 is flying backwards.



Satellite Surface Illumination

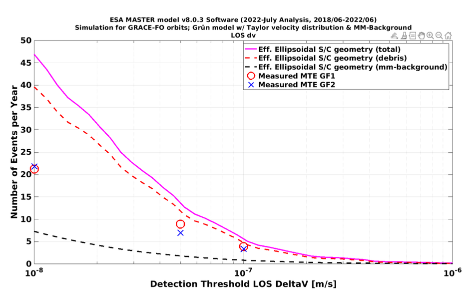
Different surfaces of the spacecraft are direclty illuminated (intersection with sun vector) over one orbit and over the year. The events marked in red likely indicate disturbances on the satellite platform, which have a small LRI Δv, but are often reported with large Δv in ACC data. These are not expected to be micrometeorites. They cluster, e. g., at sun-shaddow transitions.



Green: Events with high consistency between LRI and ACC Δv are evenly distributed, i. e., not correlated to argument of latitude position. They are likely micrometeorites.

Micrometeorite Background: ESA MASTER Software

Comparing the incidence rate of MTEs in the LRI data with predictions from the so-called Grün model (in ESA Master) reveals that the measured rate is slightly below the prediction (for $\Delta v > 5 \cdot 10^{-8}\,\mathrm{m/s}$). However, we regard the difference within the uncertainty of the model. Incidence rates with detection threshold below 5e-8 are expected to be lower, since the LRI noise prevents proper detection of MTEs.

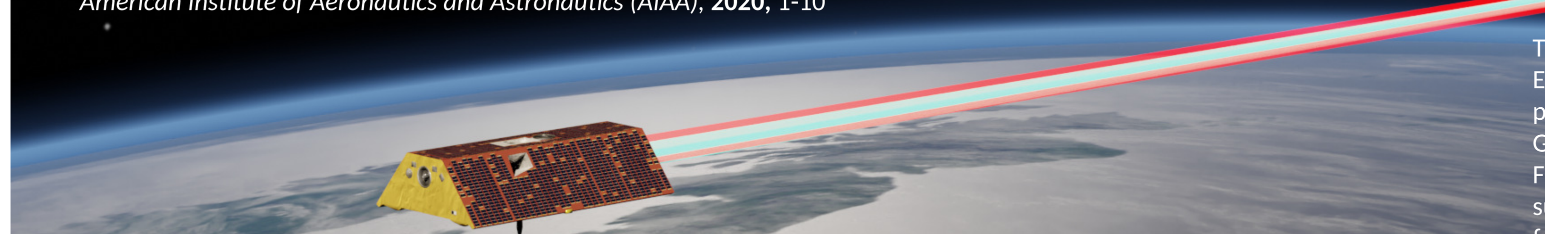


Contact Information

eMail: malte.misfeldt@aei.mpg.de
Web: www.aei.mpg.de

Further Reading

[1] **Abich, K. et al.,** In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer. *Physical Review Letters, American Physical Society (APS)*, **2019**, 123
[2] **Misfeldt, M. et al.,** Disturbances from Single Event Upsets in the GRACE Follow-On Laser Ranging Interferometer, *Preprint*, **2023**, arXiv:2302.07681
[3] **Misfeldt, M. et al.,** Scale Factor Determination for the GRACE Follow-On Laser Ranging Interferometer Including Thermal Coupling. *Remote Sensing, MDPI AG*, **2023**, 15
[4] **Nicklaus, K. et al.,** Towards NGGM: Laser Tracking Instrument for the Next Generation of Gravity Missions. *Remote Sensing, MDPI AG*, **2022**, 14, 4089
[5] **Müller, V. et al.,** Comparing GRACE-FO KBR and LRI Ranging Data with Focus on Carrier Frequency Variations. *Remote Sensing, MDPI AG*, **2022**, 14, 4335
[6] **Wegener, H. et al.,** Tilt-to-Length Coupling in the GRACE Follow-On Laser Ranging Interferometer. *Journal of Spacecraft and Rockets, American Institute of Aeronautics and Astronautics (AIAA)*, **2020**, 1-10



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

The authors would like to thank the DFG (Project-ID 434617780, SFB1464); Clusters of Excellence "Quantum Frontiers: Foundations and Applications in Metrology" (EXC-2123, project number: 390837967); the European Space Agency ESA in the framework of Next Generation Gravity Mission development and ESA's third-party mission support for GRACE-Follow On (RFP/3-17121/21/I-DT-lr); the Max Planck Society MPG for future mission support (M.IF.A.QOP18108) and in the framework of the LEGACY cooperation on low-frequency gravitational-wave astronomy (M.IF.A.QOP18098).