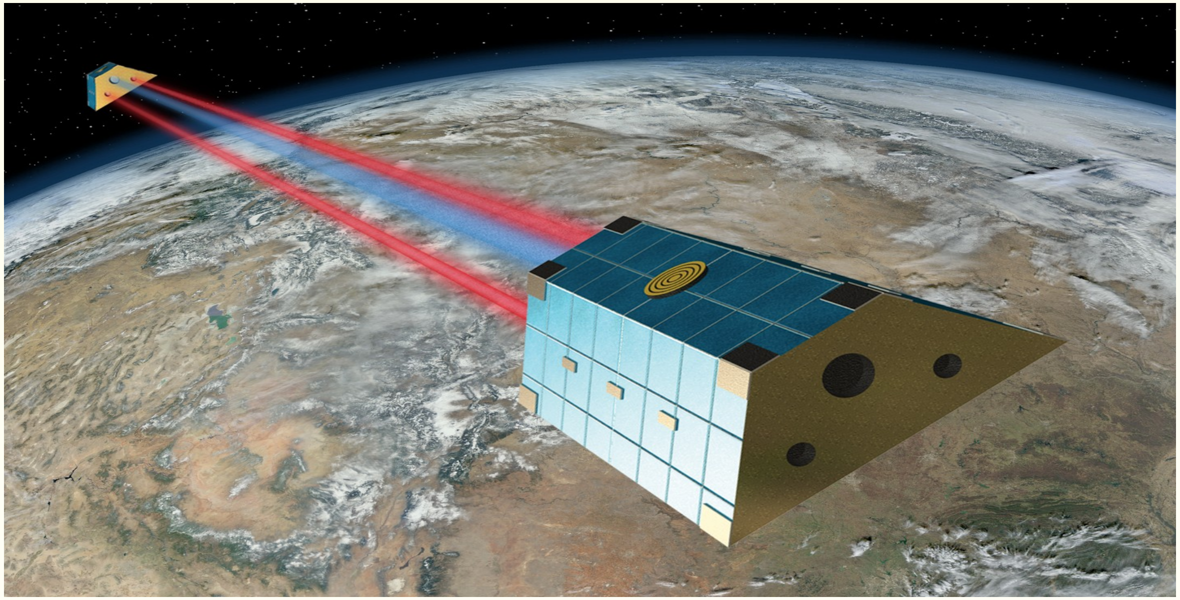


Laser Ranging Interferometer on GRACE Follow-On: Current Status

Vitali Müller for the LRI Team

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

GRACE Follow-On

- Collaboration between NASA (Germany) and GFZ (Germany)
- Launched on 22 May 2018
- SpaceX Falcon 9 launcher, ride-share with 5 Iridium NEXT satellites

https://www.youtube.com/watch?v=Tvdz5yFSwCY

Launching U.S./German GRACE-FO (live broadcast)

- Nearly perfect orbit insertion of GRACAE FO satellites

Payload of GFO similar to GRACE, except ...

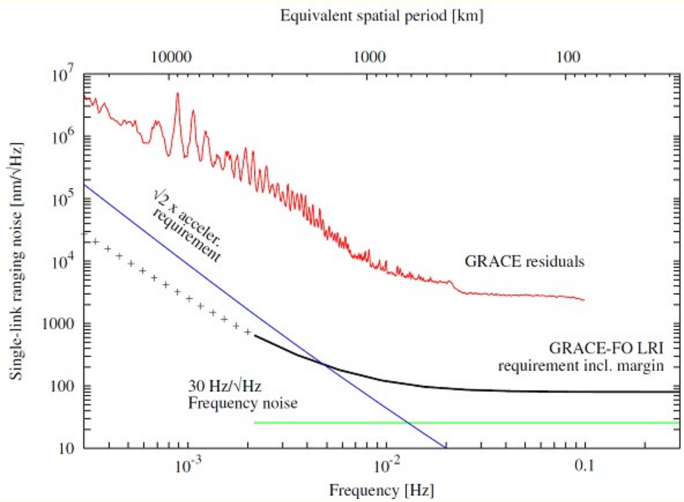
Laser Ranging Interferometer (LRI)

Technology demonstrator on-board GRACE Follow-On

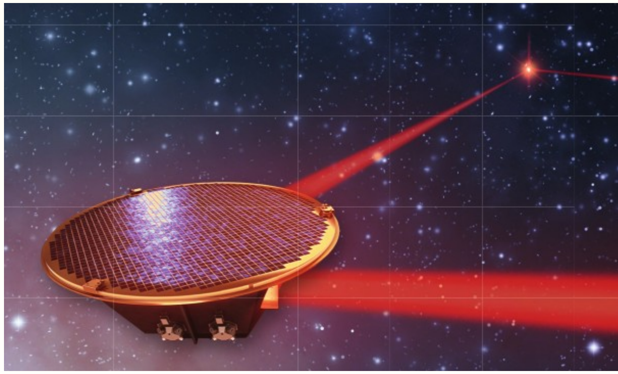
- Inter-satellite biased ranging with a noise req. of

$$\lesssim 80\mathrm{nm}/\sqrt{\mathrm{Hz}} \times \mathrm{NSF}(f)$$

- First optical inter-satellite ranging interferometer
  282 THz ~ 1064 nm
- Heterodyne Interferometry: 4...16 MHz
- Transponder scheme in comparison to Dual One-Way Ranging
- Weak-light interference: picoWatt level (worst-case)
- LRI offers yaw & pitch information w.r.t. line-of-sight



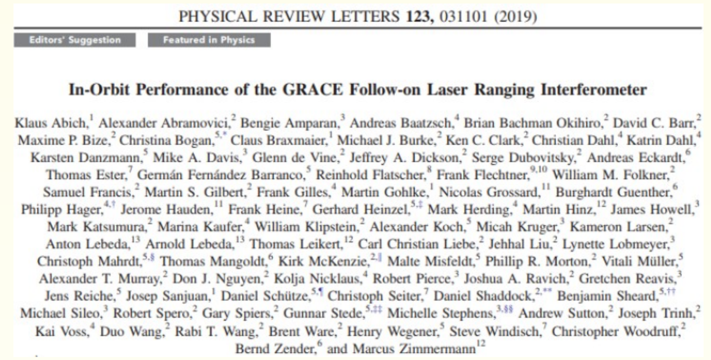
- Two independent measurements of biased range by LRI & KBR in parallel
  - LRI demonstrator less strict requirements on lifetime, reliability, redundancy
- Joint US & German project
  -  : Laser Ranging Processor LRP (JPL), Laser (Tesat), Frequency Stabilization Reference (Cavity, Ball Aerospace)
  -  : Optical Bench (STI), Photoreceiver (DLR) Triple Mirror & Beam Steering (STI/Airbus)
- Important step towards inter-S/C laser interferometery for future missions
  - Gravimetric (GRACE-2, NGGM)
  - Gravitational Wave detection (LISA)



LISA satellites, S. Barke / U Florida

Instrument Status

- The LRI is functional and delivers low-noise measurements of inter-satellite range (& range-rate)
  - After post-processing: noise level at 200 pm/rtHz above 1 Hz Fourier frequency
  - Paper on LRI's in-orbit performance published incl. basic strategy for deglitching



PHYSICAL REVIEW LETTERS 123, 031101 (2019)

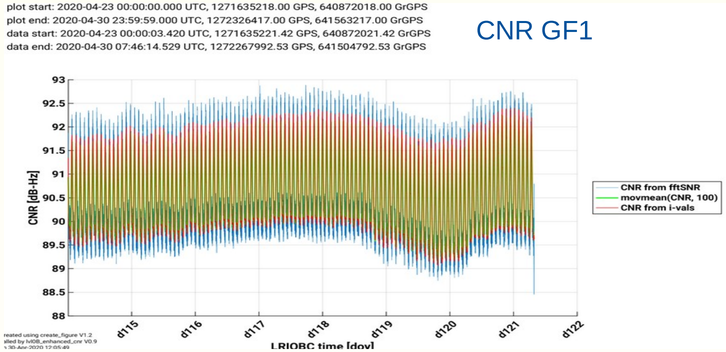
Editors' Suggestion | Featured in Physics

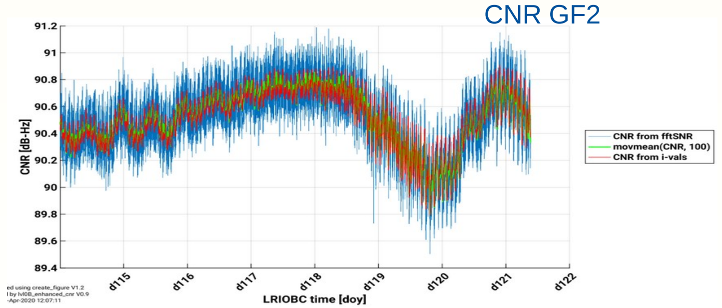
In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer

Klaus Abich,[1] Alexander Abramovici,[2] Bengie Amparan,[3] Andreas Baatzsch,[4] Brian Bachman Okihiro,[2] David C. Barr,[2] Maxime P. Bize,[2] Christina Bogan,[5,*] Claus Braxmaier,[1] Michael J. Burke,[2] Ken C. Clark,[2] Christian Dahl,[4] Katrin Dahl,[4] Karsten Danzmann,[5] Mike A. Davis,[3] Glenn de Vine,[2] Jeffrey A. Dickson,[2] Serge Dubovitsky,[2] Andreas Eckardt,[6] Thomas Ester,[7] Germán Fernández Barranco,[5] Reinhold Flatscher,[8] Frank Flechtner,[9,10] William M. Folkner,[2] Samuel Francis,[2] Martin S. Gilbert,[2] Frank Gilles,[4] Martin Gohlke,[1] Nicolas Grossard,[11] Burghardt Guenther,[6] Philipp Hager,[4,†] Jerome Hauden,[11] Frank Heine,[7] Gerhard Heinzel,[5,‡] Mark Herding,[4] Martin Hinz,[12] James Howell,[3] Mark Katsumura,[2] Marina Kaufer,[4] William Klipstein,[2] Alexander Koch,[5] Micah Kruger,[3] Kameron Larsen,[2] Anton Lebeda,[13] Arnold Lebeda,[13] Thomas Leikert,[12] Carl Christian Liebe,[2] Jehhal Liu,[2] Lynette Lobmeyer,[3] Christoph Mahrdt,[5,§] Thomas Mangoldt,[6] Kirk McKenzie,[2,∥] Malte Misfeldt,[5] Phillip R. Morton,[2] Vitali Müller,[5] Alexander T. Murray,[2] Don J. Nguyen,[2] Kolja Nicklaus,[4] Robert Pierce,[3] Joshua A. Ravich,[2] Gretchen Reavis,[3] Jens Reiche,[5] Josep Sanjuan,[1] Daniel Schütze,[5,¶] Christoph Seiter,[7] Daniel Shaddock,[2,**] Benjamin Sheard,[5,††] Michael Sileo,[3] Robert Spero,[2] Gary Spiers,[2] Gunnar Stede,[5,‡‡] Michelle Stephens,[3,§§] Andrew Sutton,[2] Joseph Trinh,[2] Kai Voss,[4] Duo Wang,[2] Rabi T. Wang,[2] Brent Ware,[2] Henry Wegener,[5] Steve Windisch,[7] Christopher Woodruff,[2] Bernd Zender,[6] and Marcus Zimmermann[12]

- Satellite pointing information in yaw and pitch can be derived from LRI's steering mirror data

- No degradation of instrument performance visible from launch until now (May 2020)
  - Signal-to-noise ratio (carrier-to-noise density, CNR) well above the requirement of 70 dB-Hz
  - LRI has no consumables





- LRI data (level1a+b) is publicly available together with other GRACE-FO data through
  - https://podaac.jpl.nasa.gov/
  - https://isdc.gfz-potsdam.de/

- Since LRI is a new instrument, a few issues with the level 1a+1b data have not been resolved yet
  - LRI team is working together with SDS/JPL to improve data quality

- Instrument characterization is ongoing
  - Tilt-to-length coupling

Details on some points are shown on next slides

LRI data availability

- Table: each row is a month;
  green means ranging data has been recorded
  - July – December 2018: Anomaly with IPU on GF2
  - Feb – March 2019: On-Board Computer on GF2 issue
  - April 2019: 4 days of diagnostic scans by LRI
  - December 2019: 2 days of diagnostic scans
  - January and February 2020:
    hickup with GPS/On-Board-Computer on GF2

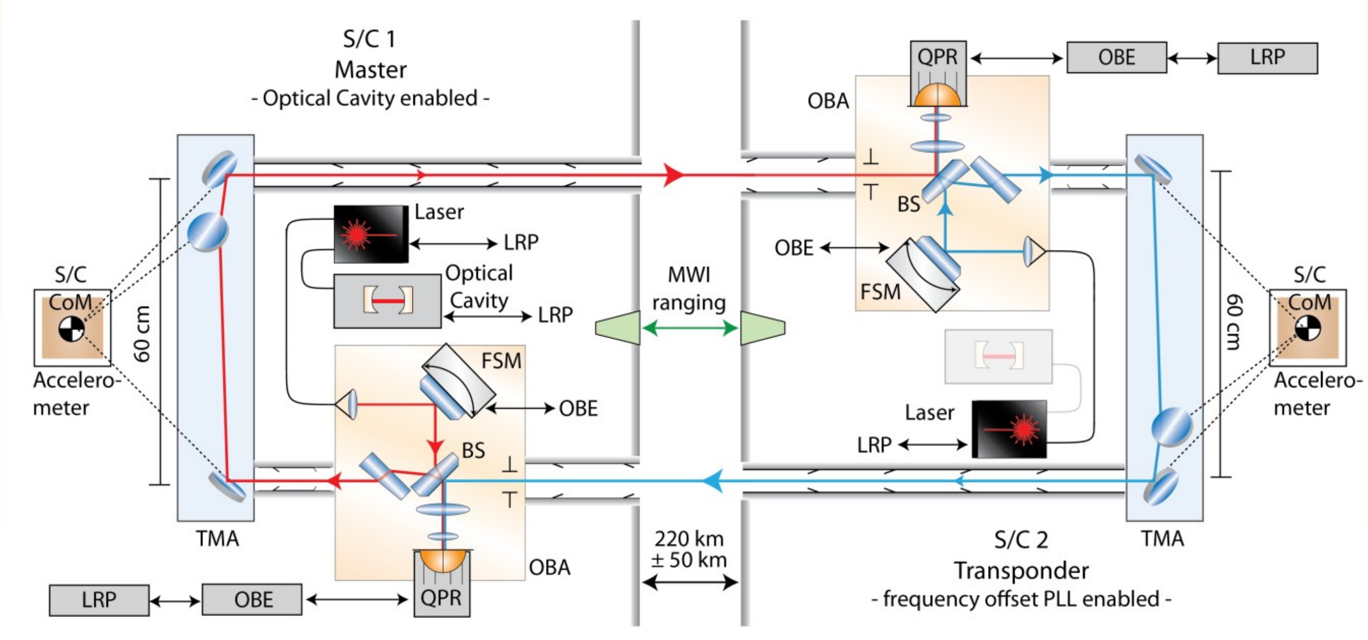
Large gaps not related to LRI, caused by non-nominal pointing (e.g. safe mode) of S/C

Known issues with LRI RL04 Level1A+B data

- Level1A:
  - LRI Housekeeing (LHK1A) has a few columns with incorrect time-tag, e.g. values have not been converted properly from clock ticks to nanoseconds
  - the time-tags of the LRI ranging data (LRI1A) have 1 nanosecond resolution, however, LRI samples are recorded at a non-integer nanosecond rate.
  - ...
- Level1B: most interesting for geodesy community, can be used in gravity field recovery
  - LRI1B data product: 2 second regular sampling in GPS time-frame, biased instantaneous range
  - RL04: the conversion from LRI1A to LRI1B comprises re-scaling (conversion from phase to length), time-shifting, and deglitching
  - The current deglitching scheme employed in RL04 LRI processing has some deficiencies, which yields – on some days -residual glitches and/or incorrect scale and/or incorred time-offset
  - GRACE FO Science Data System (SDS) is working to resolve the issue
- Some issues in level1 data might only be resolved in the next release (RL05) according to current assessment by SDS
  - Thus, if you are working with GRACE Follow-On LRI data, we are happy to share work-arounds and give support where possible. Write to vitali.mueller@aei.mpg.de
- The AEI Hannover has derived an alternative LRI1B dataset for January 2019, which can be used to assess the LRI data quality
  - See https://meetingorganizer.copernicus.org/EGU2020/EGU2020-15569.html
  - Improved deglitching & light-time-correction, different scale factor estimation, ….

AEI is preparing to generate more LRI1B datasets

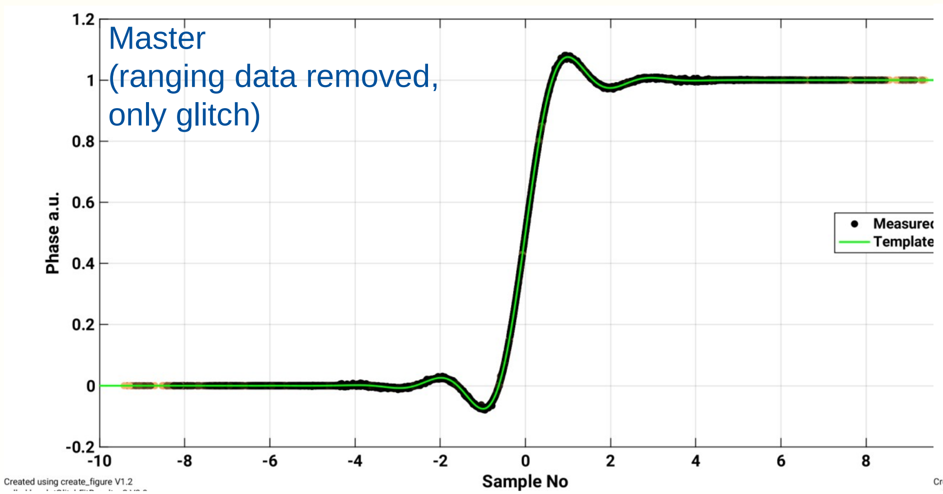
LRI Transponder Scheme

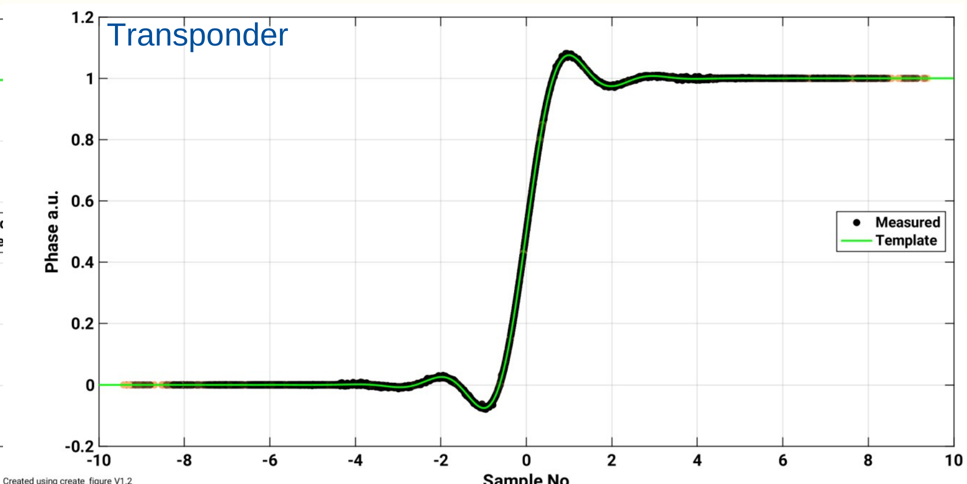


- Role of Master and Transponder interchangeable
  - Both S/C equipped with frequency stabilization unit (Cavity)
- Transponder S/C
  - High-gain frequency-locked loop with 10 MHz frequency offset
    → keeps frequency constant & phase variations< 100 pm/√Hz
    → phase readout sensitivity a few 10 pm/√Hz
- Master S/C
  - Active laser frequency stabilization
  - Measured Frequency
    ~ 2x Doppler + frequency offset
- (Laser) frequency noise suppression in the optical domain (different for DOWR)
  - Single data stream for ranging
  - Subtraction of linear phase ramp in L1A → L1B

LRI Phase Jumps / Glitches by ACT usage

- LRI ranging data exhibits steps/jumps/glitches, which are correlated with / caused by attitude control thruster (ACT) usage
  - Mainly roll thrusters on the master satellite, other thrusters and thrusters on transponder satellite cause jumps only sporadically
- Most of the phase jumps can be removed from the ranging data in a “physical way”, because the same jump appears with the same amplitude on both satellites.
  - Shape of the jump = step response processed by a decimation (low-pass) filter
  - The LRI on transponder is supposed to measure zero (when ramp removed), but it measures a jump.
  - Forming the difference “Transponder-Phase – Master-Phase” with correct time-delay
    - would completely remove the jumps, if sampling rate of LRI range data would be >> 10 Hz.





Usually, both satellites measure the same glitch,

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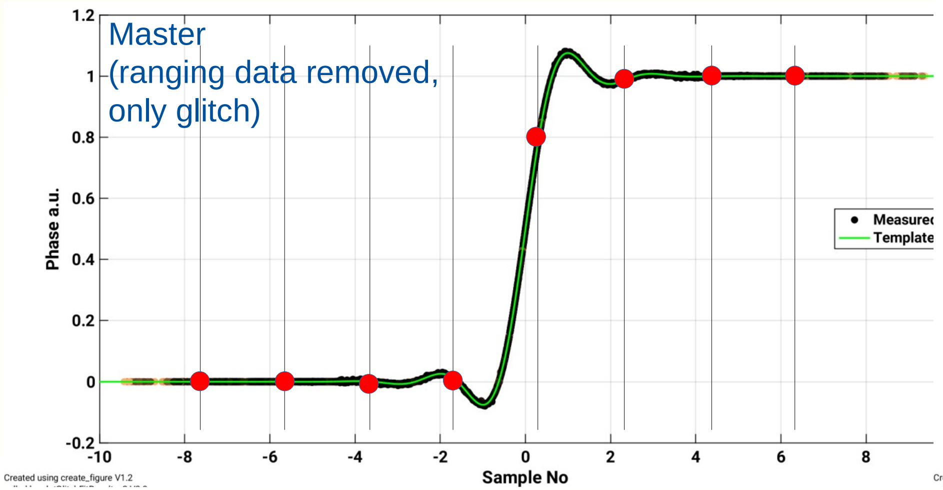
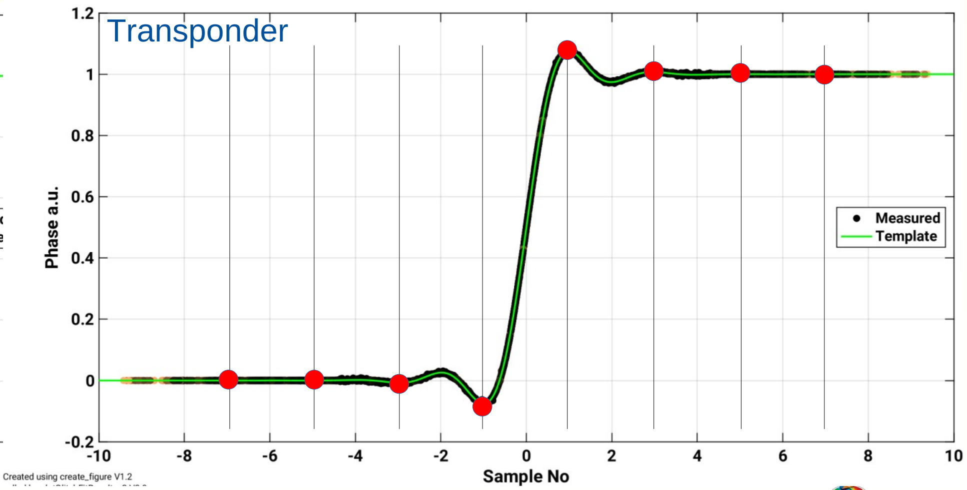
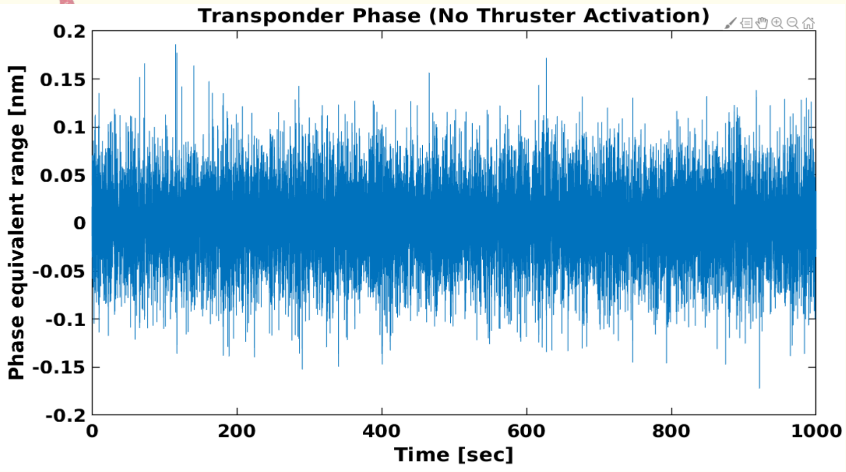
    - would completely remove the jumps, if sampling rate of LRI range data would be >> 10 Hz.
  - Due to 10 Hz sampling rate & occurrence of step response not locked to sampling clock
    - Phase jumps appear different on master and transponder (see red dots)

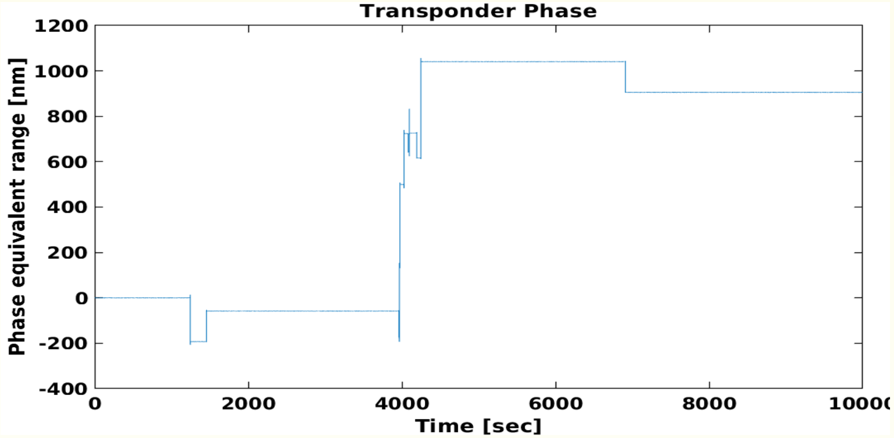




Usually, both satellites measure the same glitch, but sampled differently.

LRI Transponder Phase & Deglitching Transponder-Fit





On short time scales without attitude thruster activations

- Noise below 100 pm/√Hz

On longer time scales:

- Phase jumps appear with random amplitude (higher amplitudes are less likely, most jumps < 1 µm)
- Correlated with attitude control thruster usage, mainly roll thruster on master
- Transponder phase jumps appear with same amplitude on master side
  → feature of light that propagates between S/C

Deglitching algorithm

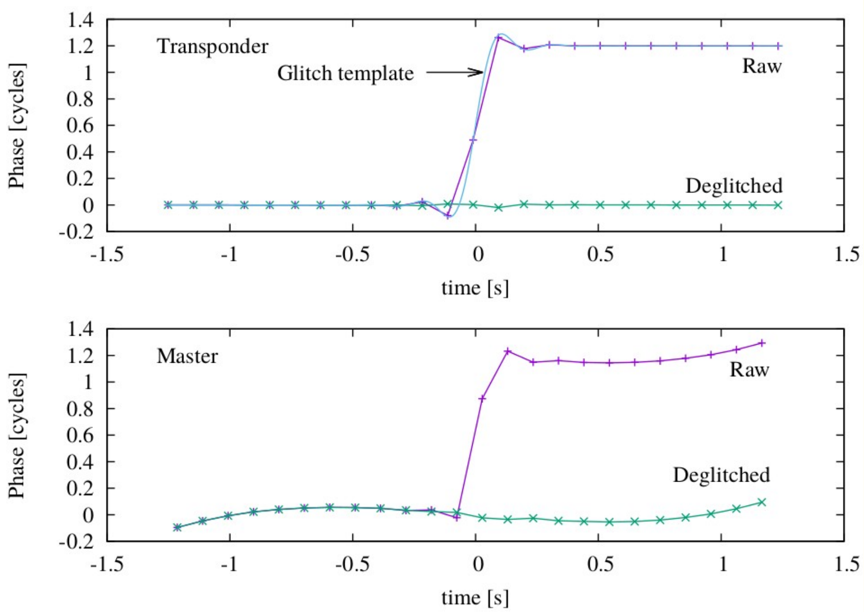
- Fit an analytical model (“template”) of the glitch to the transponder data to obtain amplitude and time offsets;
- usually single phase jump with 2-parameter-fit: 1 amplitude, 1 time offset
- sometimes double-phase jump with two close-by jumps (separation < 100 msec);
  4-parameter-fit: 2 amplitudes, 2 time offsets

Deglitching step 1: fit model parameters to transponder data

LRI Phase Jumps Removal

Step 2: Remove phase jump using glitch model from master and transponder

- subtraction from master phase re-uses parameters from transponder-fit, but additional delay between master and transponder clock is estimated
  - This delay is highly correlated with USO clock difference (CLK1B_C.eps_time-CL1B_D.eps_time)



- Deglitching algorithm at AEI reduces phase jump by a factor of ~1000.

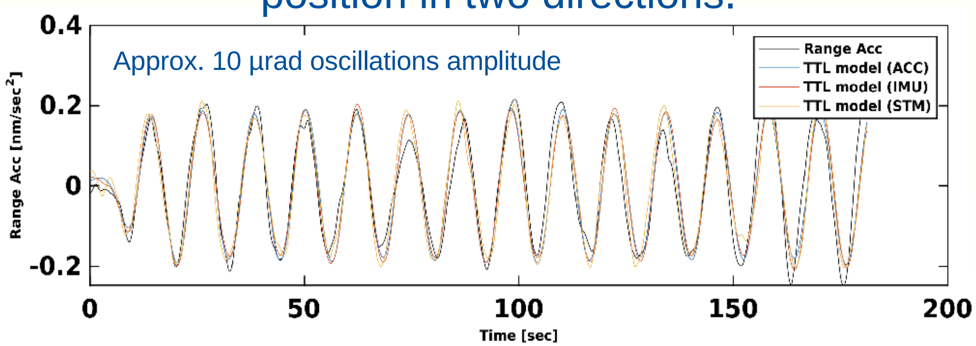
- LRI team has ideas to mitigate these phase jumps at the flight software level
  - Method 1: change parameters of laser ranging processor for laser frequency control
  - Method 2: update the flight software to use phase-lock instead of frequency-lock

Mitigation has currently low priority, since post-processing is known to work

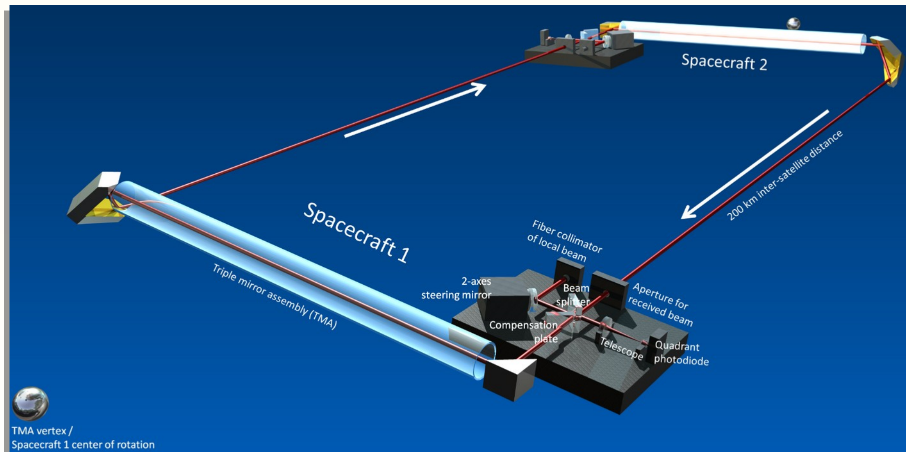
LRI: Attitude Induced Errors

LRI was designed to have a small rotation-to-pathlength coupling

- Due to triple mirror assembly (TMA) and optical bench working principle
- TMA vertex (“phase center”) separated from physical structure
  - → co-located with CoM/ACC reference point,
  - → lever arm expected to be of the order of ~100 µm (x,y,z)
  - → coupling at the level of ~ 100 µm/rad and 100 µm/rad² in yaw & pitch
  - → KBR antenna offset correction: a few 100µm/rad & 1.4m/rad² in yaw & pitch
- Still expected to be dominating noise source at low frequencies
- Long-term ranging data & center-of-mass calibration maneuvers
  - → expectations are met.
- Since the offset between TMA vertex and ACC RP is considered to be static, LRI coupling factors are useful as an independent mean to track the S/C center of mass position in two directions.



Center of Mass Calibration Maneuver; Pitch rotations
Jan 16 2019; Fitted coupling approx. 96 µm/rad
Ranging data band-pass filtered



LRI can provide CoM position information for GF2, where ACC is unhealthy

LRI: Attitude Induced Errors

Paper (accepted) on this topic will appear soon in Journal of Spacecraft and Rockets

Estimating Tilt-to-Length Coupling in the GRACE Follow-On Laser Ranging Interferometer

Henry Wegener * and Vitali Müller† and Gerhard Heinzel‡ and Malte Misfeldt§
Max Planck Institute for Gravitational Physics (Albert Einstein Institute), 30167 Hannover, Germany
Leibniz Universität Hannover, 30167 Hannover, Germany

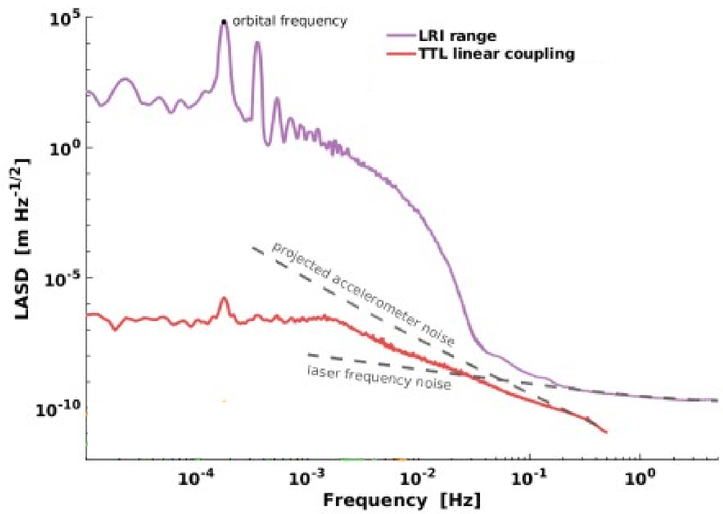
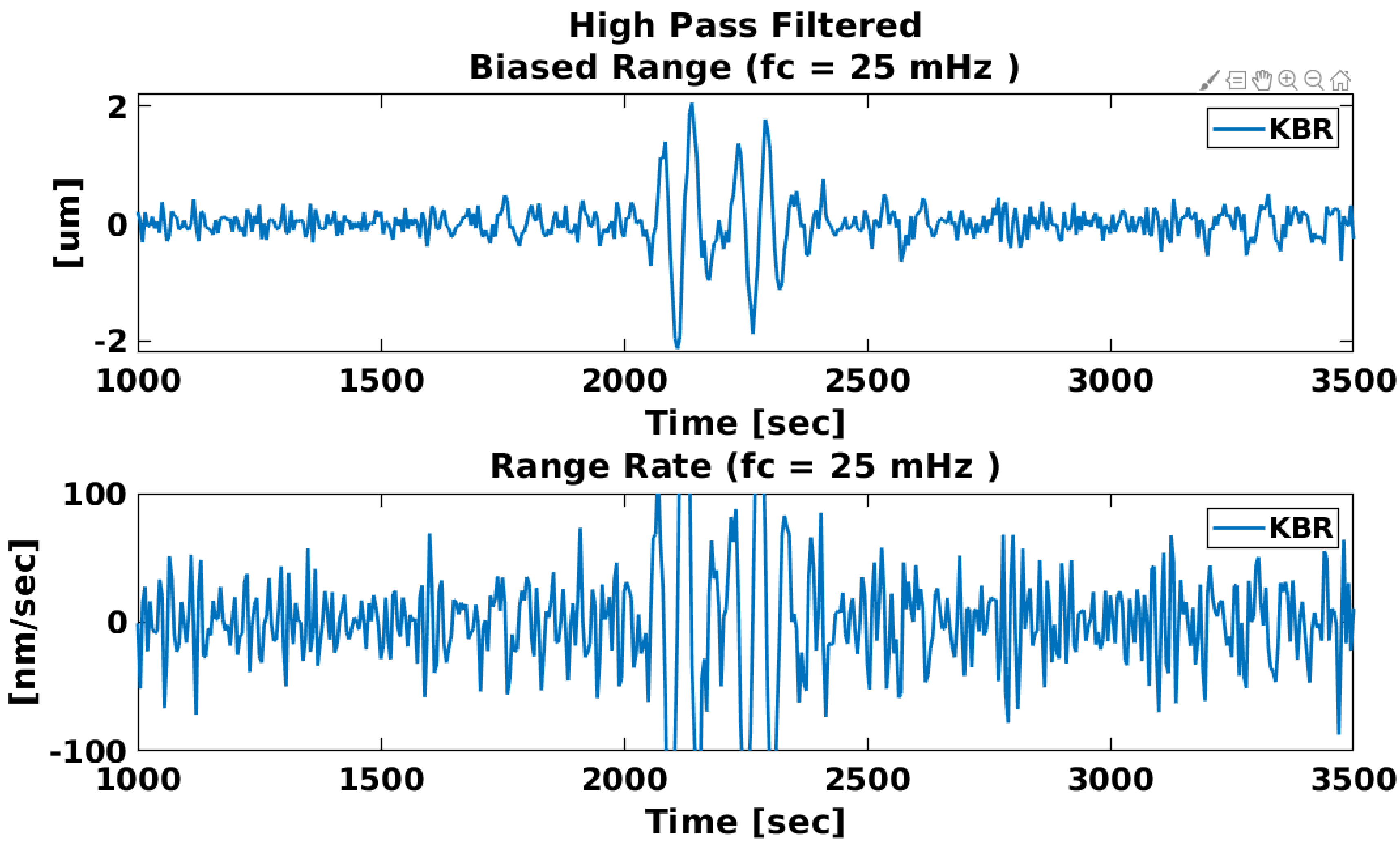


Fig. 7 Amplitude spectral density of LRI range and TTL error, from a 9-day segment during April 2019. Linear TTL coupling is based on our estimation results from the CMC executed on 24 April 2019 (cf. table 1).

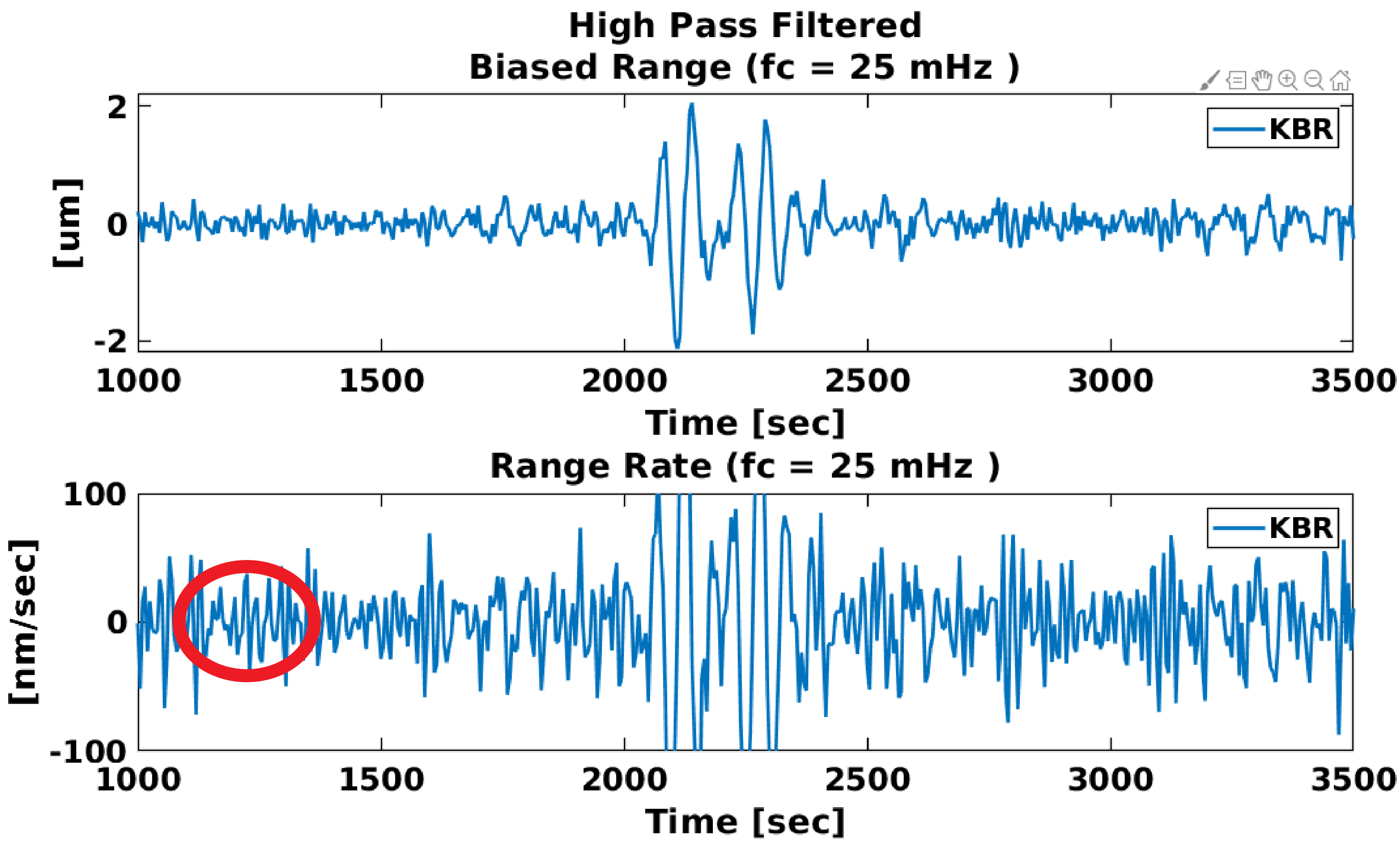
Figure illustrates the attitude-induced errors in the range spectrum

LRI Signal and Noise – Time Domain



Which parts are noise and which parts are signal?

LRI Signal and Noise – Time Domain



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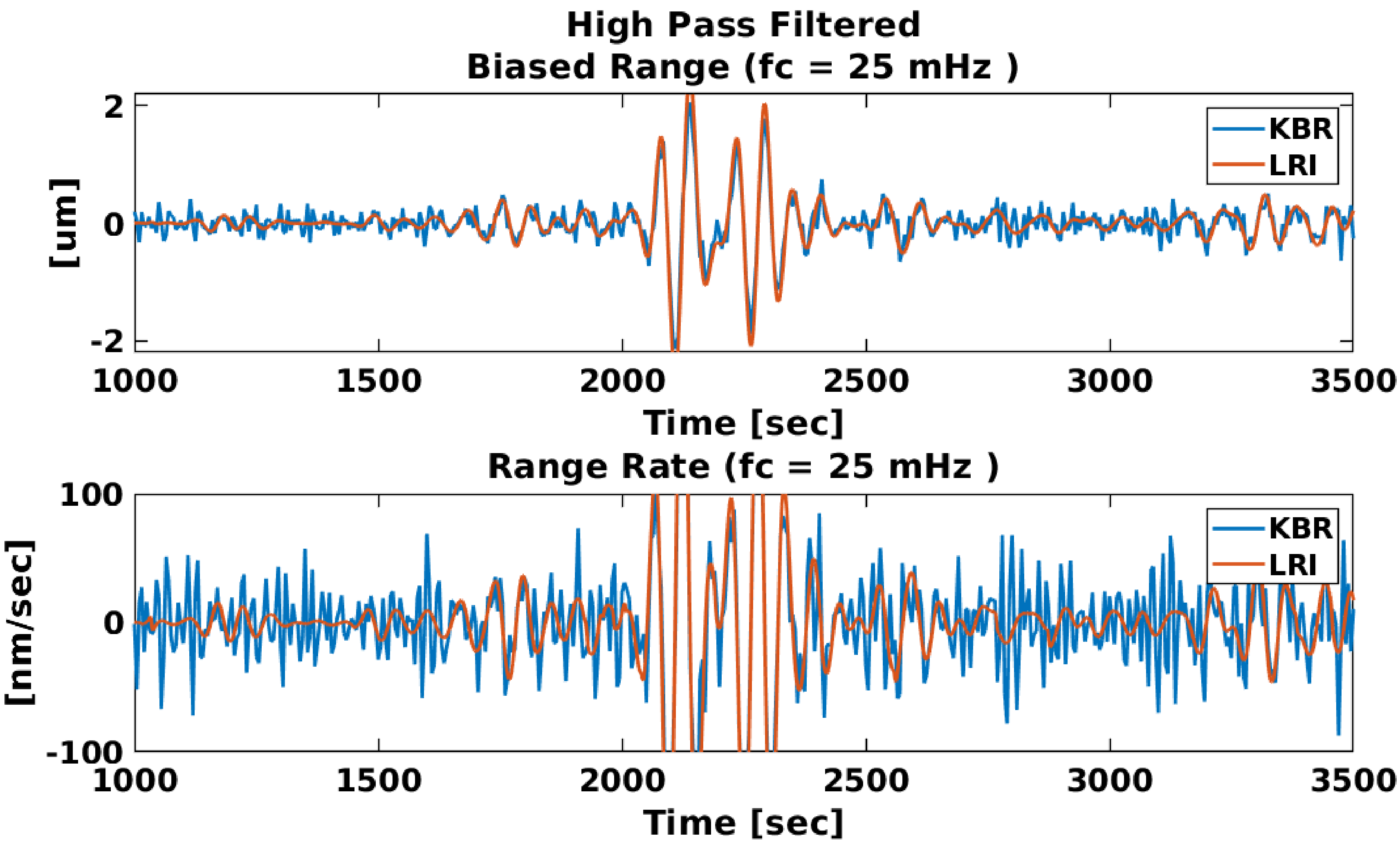

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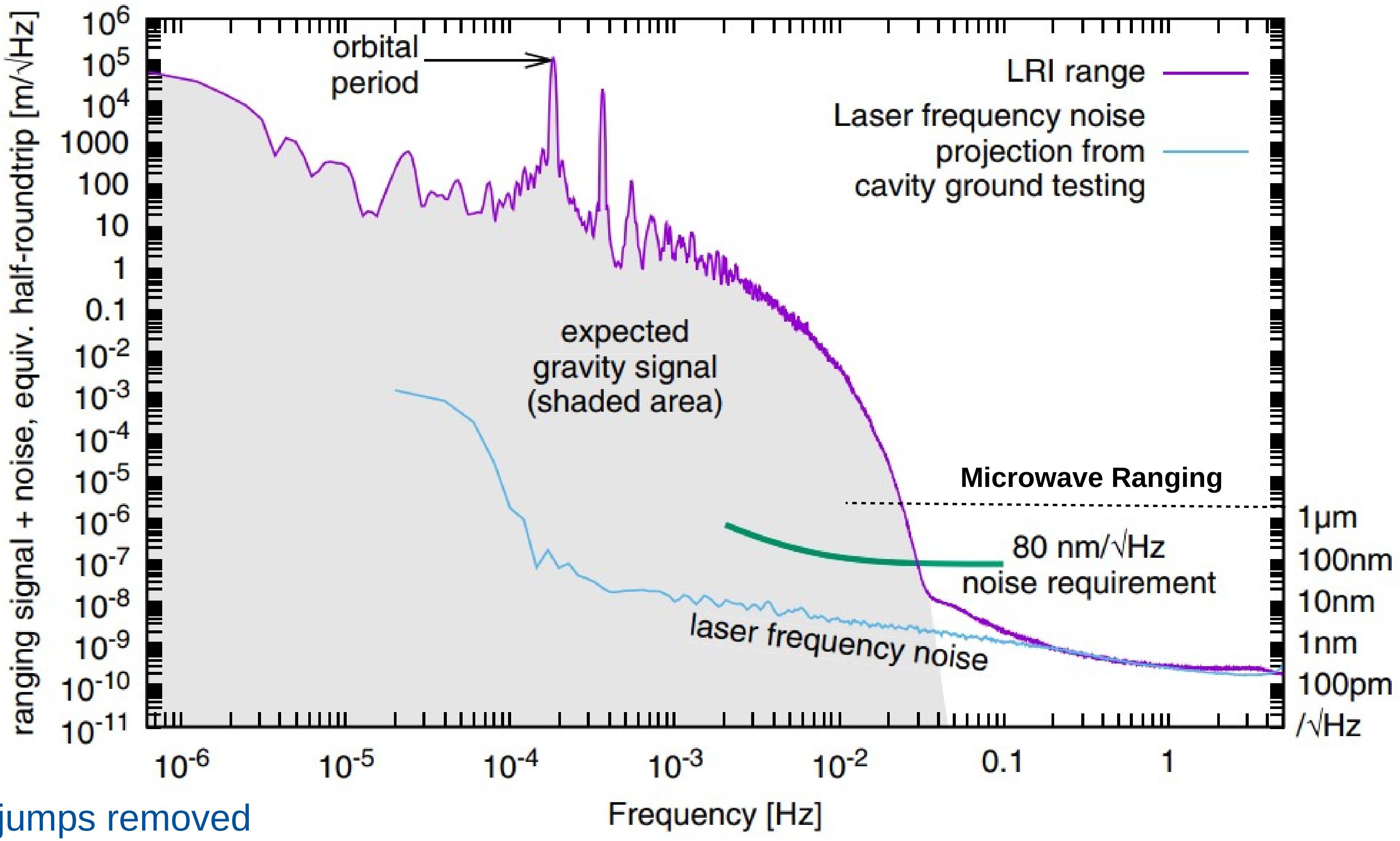
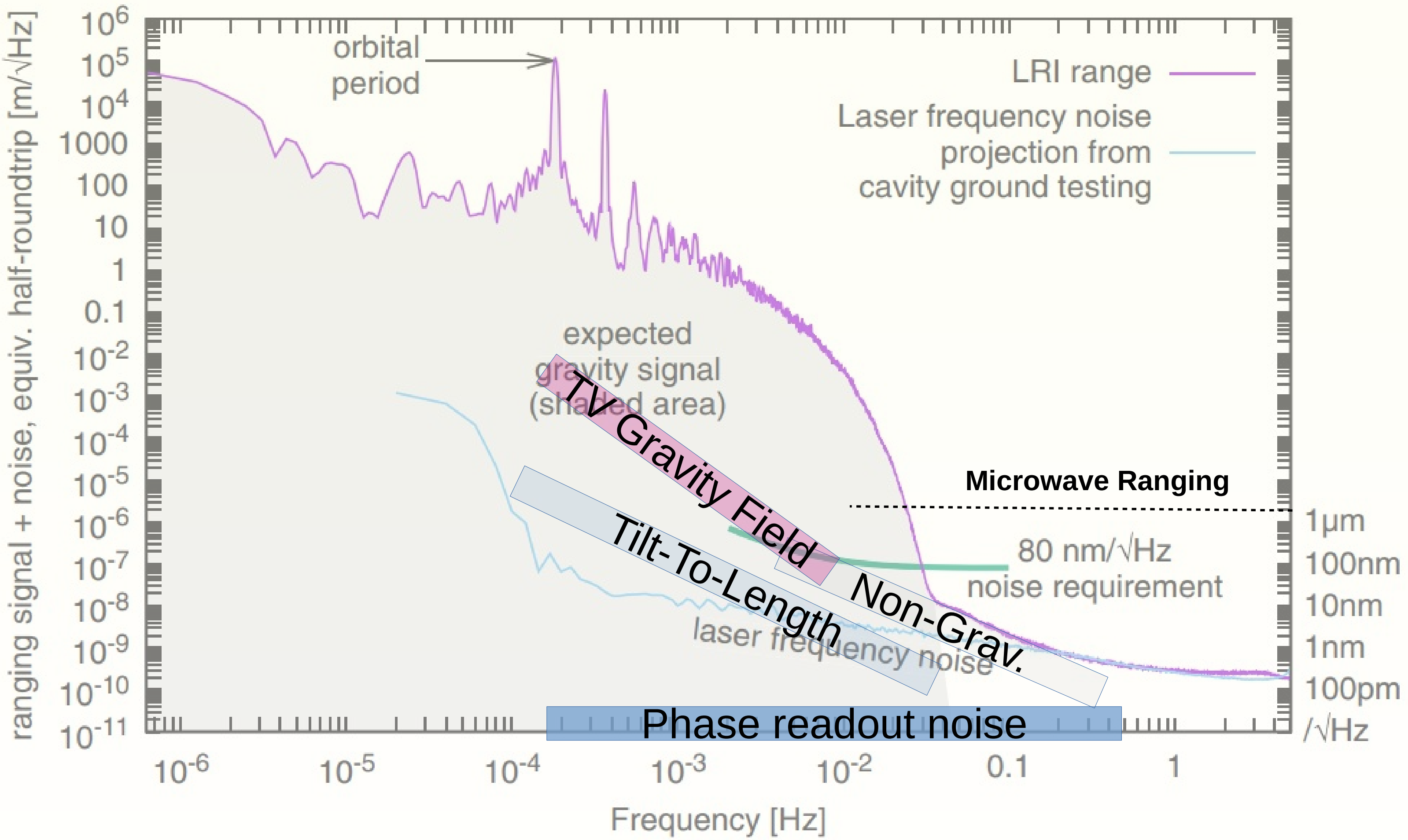
LRI Signal and Noise



- Phase jumps removed
- Laser Frequency Noise limits LRI at high frequencies
- Instrument noise at low frequencies (< 35 mHz) difficult to evaluate
- Noise as low as 200 pm/√Hz at high frequencies > 1 Hz

LRI resolves within 1 second distance changes of the size of a single Helium atom

LRI Signal and Noise



- Range changes from non-gravitational accelerations are present between 35 .. 200 mHz
- Tilt-To-length coupling is projected to limit at low frequencies (< 10 mHz)
- Time-Variable (TV) gravity field signal much smaller than total measured signal

Effect of scale factor uncertainty not shown here

Modifications of LRI for future missions

- Disclaimer: Points on this slide may not represent the views of the whole "LRI team".

- The GRACE Follow-On Laser Ranging interferometer (tech-demo) works very well
  - Provides low-noise measurements of the inter-satellite range
  - Provides yaw and pitch measurements of satellite attitude with respect to line-of-sight
  - No degradation of performance observed within the first ~ 2 years of in-orbit operation
- LRI could fly as-is in future GRACE FO-like missions, but some lessons learned
  - More thorough characterization & mitigation of (thruster-induced) vibrations onto LRI
    - avoid LRI phase jumps
    - similar problem with regard to accelerometer
  - Iodine frequency reference instead of cavity would eliminate scale factor uncertainty for LRI
    - use gold standard/definition of "1 meter"
  - Dedicated laser link acqusition sensor could reduce complexity of current laser link acquisition scheme
  - Feedback of LRI yaw and pitch pointing information into satellite attitude control could reduce attitude-induced ranging errors

A future mission could use LRI as only mean for ranging, LRI would need redundancy

Summary & Remarks

- LRI ranging noise well below the 80 nm/√Hz requirement
  - As low as 200 pm/√Hz at high frequencies (>1 Hz)
- Observed phase jumps correlated with attitude thruster activations
  - Phase jumps can be removed from the data & are partly removed in Level-1B
  - Other outliers such as cycle slips are very rare

- LRI provides attitude information in yaw and pitch w.r.t. the line-of-sight
  - An alternative instrument to track CoM shifts (in two directions)
- Carrier-To-Noise ratio (signal strength) very close to the maximum
  - Optimal alignment of laser beams, low optical losses
- No degradation of signals observed between June 2018 and (today) May 2020

- LRI demonstrated feasibility of inter-spacecraft laser interferometry
  - Ready to become a primary instrument in a NGGM or GRACE-2 mission
  - Minor modifications have been discussed

Summary & Remarks II

Thank you for your attention