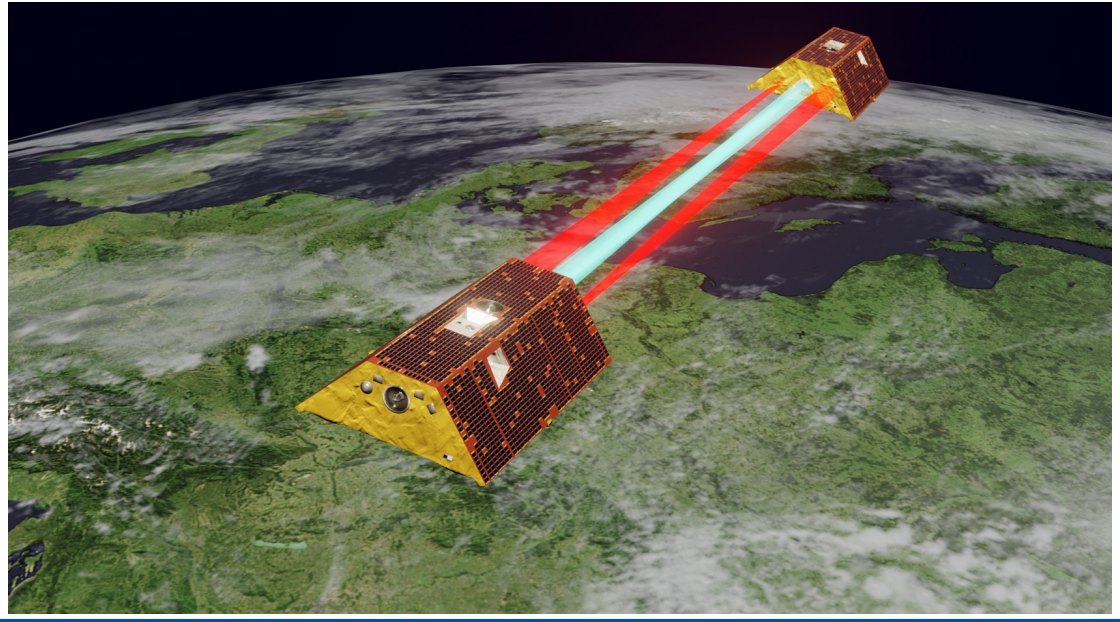
Abstract GSTM2024-70

Recent Analyses with Alternative LRI1B Datasets of AEI

by Laura Müller, Vitali Müller, Yihao Yan, Malte Misfeldt, Pallavi Bekal, and Gerhard Heinzel



Laura Müller (laura.mueller@aei.mpg.de)

Image: Malte Misfeldt. Textures: NASA, the blue marble

Scan Me

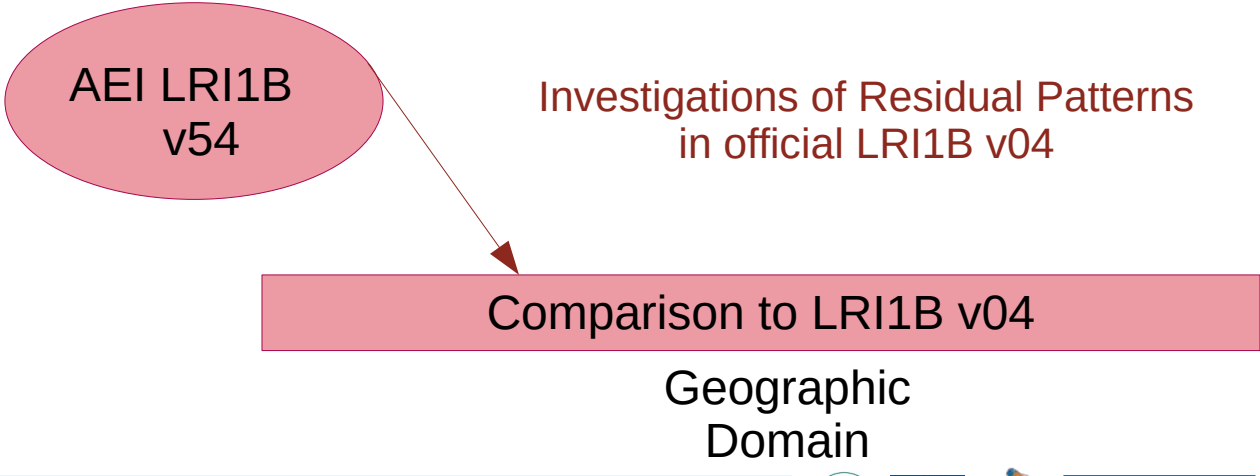
Overview

- AEI LRI1B v54 is available for all month where LRI was able to track (June 2018 – June 2023)
- Sub-release 2024-09-01 is available with 0.5 Hz and 0.2 Hz sampling
- 0.2 Hz dataset is produced by using the KBR CRN filter,
  to allow easier comparisons of the two ranging instruments
- Range rates in new datasets improved relative to previous AEI releases
  (around 10 mHz by at least a factor of 2)
- Datasets available at: https://www.aei.mpg.de/grace-fo-ranging-datasets

AEI LRI1B
v54

Overview

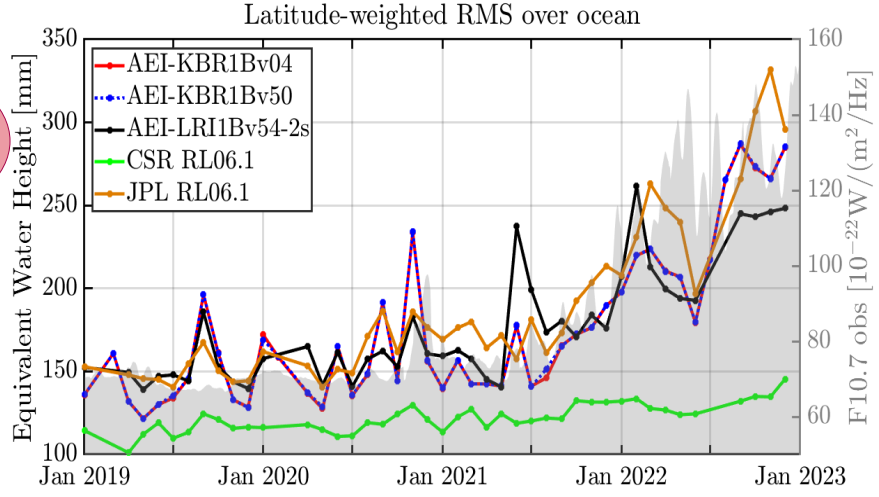
- AEI LRI1B v54 is available for all month where LRI was able to track (June 2018 – June 2023)
- Sub-release 2024-09-01 is available with 0.5 Hz and 0.2 Hz sampling
- 0.2 Hz dataset is produced by using the KBR CRN filter,
  to allow easier comparisons of the two ranging instruments
- Range rates in new datasets improved relative to previous AEI releases
  (around 10 mHz by at least a factor of 2)
- Datasets available at: https://www.aei.mpg.de/grace-fo-ranging-datasets



Overview

- Some groups reported that gravity fields from LRI exhibit slightly higher ocean RMS compared to KBR
- Also observed by AEI (black curve higher than blue or red),
  by using the Chinese gravity field recovery software GSOFT, developed at APM in Wuhan
- Differences between KBR and LRI are usually smaller than KBR solution differences between different processing centers (e.g. CSR/JPL/GFZ)

AEI LRI1B v54



Overview

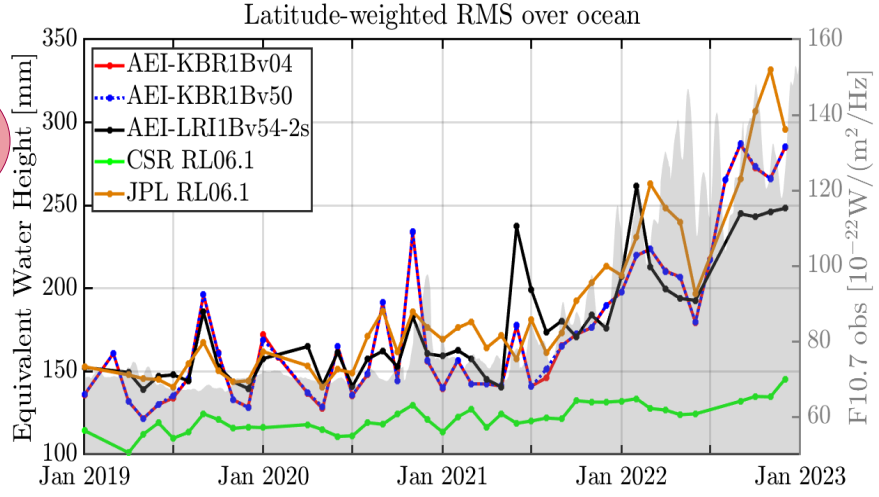
- Some groups reported that gravity fields from LRI exhibit slightly higher ocean RMS compared to KBR
- Also observed by AEI (black curve higher than blue or red), by using the Chinese gravity field recovery software GSOFT, developed at APM in Wuhan
- Differences between KBR and LRI are usually smaller than KBR solution differences between different processing centers (e.g. CSR/JPL/GFZ)

We will show some results to support the ongoing investigations.

AEI LRI1B v54

Comparison to KBR1B v04

Time Domain | Frequency Domain | Geographic Domain



Re-visiting Results from Duwe et al

- Duwe et al. found different patterns in LRI post-fit residuals when processing the official SDS LRI1B v04.
  GSTM2024-75: Poster | Wednesday, 09 Oct, 16:00–17:30

- Two of them appear in Argument of Latitude plots as:
  - Mesh patterns
  - Elliptical rings

- Remark:
  LRI CNR values in v04 are calculated with an incorrect formula. Actual CNR is not worse where elliptical rings appear.

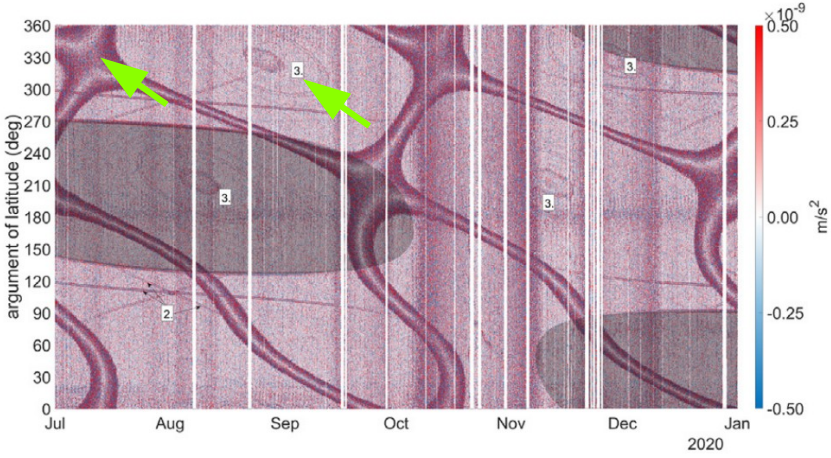


Fig. 4. (b) LRI post-fit range acceleration residuals

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (xxxx) xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Residual Patterns in GRACE Follow-On Laser Ranging Interferometry Post-Fit Range Rate Residuals

Mathias Duwe *, Igor Koch, Jakob Flury

Leibniz University Hannover, Schneiderberg 50, Hannover, 30167 Hannover, Germany

Received 14 December 2023; received in revised form 12 March 2024; accepted 14 March 2024

Abstract

The novel laser ranging interferometer (LRI) on GRACE Follow-On (GRACE-FO) provides range and range rate measurements for more than 4 years now. Since the launch of the GRACE-FO mission there were few investigations about this measurement system on the level of gravity field recovery and analysis of post-fit residuals. We applied techniques such as along-orbit-analysis or time-argument of latitude diagrams (TAL) to analyse the post-fit range rate residuals as well as the post-fit range acceleration residuals to identify unknown characteristics and systematic effects. The effects are the range rate effect, the panel effect, the Carrier-To-Noise Ratio (CNR) effect and the polar effect. The range rate effect occurs, when the range rate observation $\dot{\rho}$ of the LRI is around 0 m/s. In the TAL diagram the effect appears as a mesh pattern. The panel effect shows patterns of increased residuals when a specific satellite panel starts or stops being illuminated by the Sun. Increased residuals appear when the laser beam is aligned with the Sun. A CNR drop as well as a fluctuation of the yaw and pitch pointing angles obtained from the LRI steering mirrors is observable. Additionally, when the satellites flying into or out of the Earth shadow this effect coincides with the shadow transition effect. Another effect is the CNR effect which appears as an elliptic shape in the TAL diagram. This pattern occurs when the CNR values drop below the LRI requirements of 70 dB-Hz. All these effects have not been detected in the residuals of the GRACE-FO K-band ranging system (KBR) and therefore further investigation and studies will improve the understanding and applications of LRI technology.

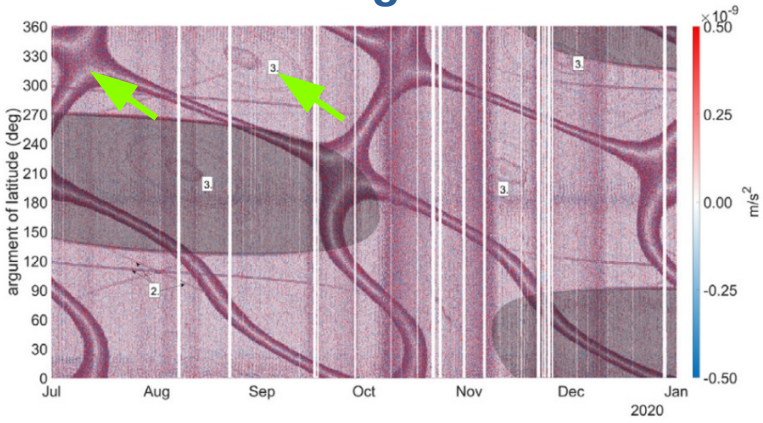
Keywords: GRACE Follow-On; Laser ranging; LRI; Post-fit residuals; Gravity field

1) Mathias Duwe et al 2024, Residual Patterns in GRACE Follow-On Laser Ranging Interferometry Post-Fit Range Rate Residuals, https://doi.org/10.1016/j.asr.2024.03.035

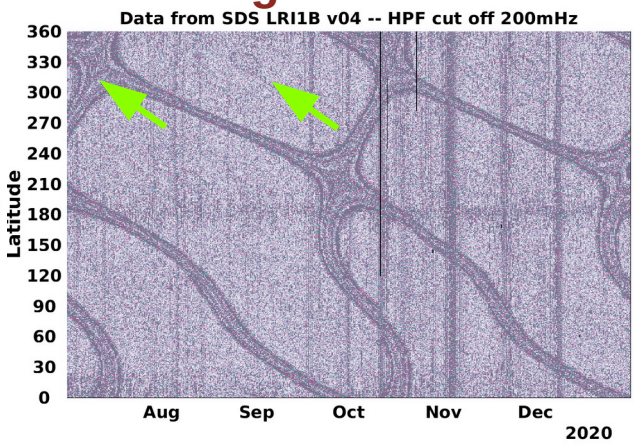
Re-Analysis of LRI Residual Patterns

- We were able to confirm these features by computing post-fit residuals from LRI1B v04 data
- AEI in-house derived LRI1B v54 does not show this features
- Diagonal lines in right plot are most likely caused by empirical parameter estimation

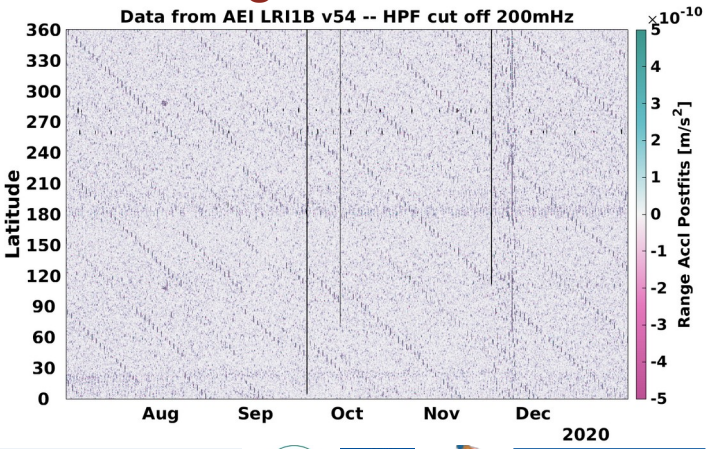
Duwe et al[1] using LRI1B of SDS



AEI using LRI1B of SDS



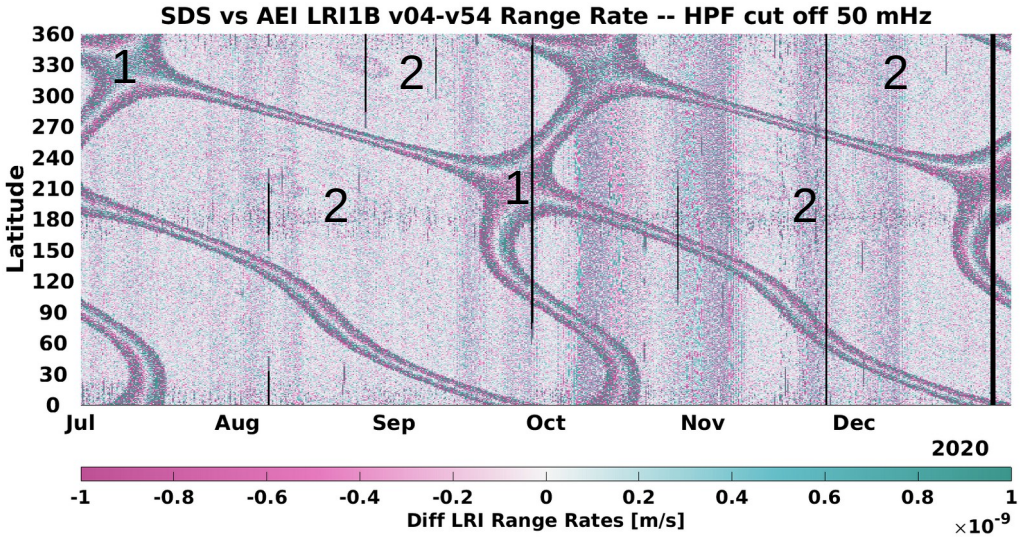
AEI using in-house LRI1B

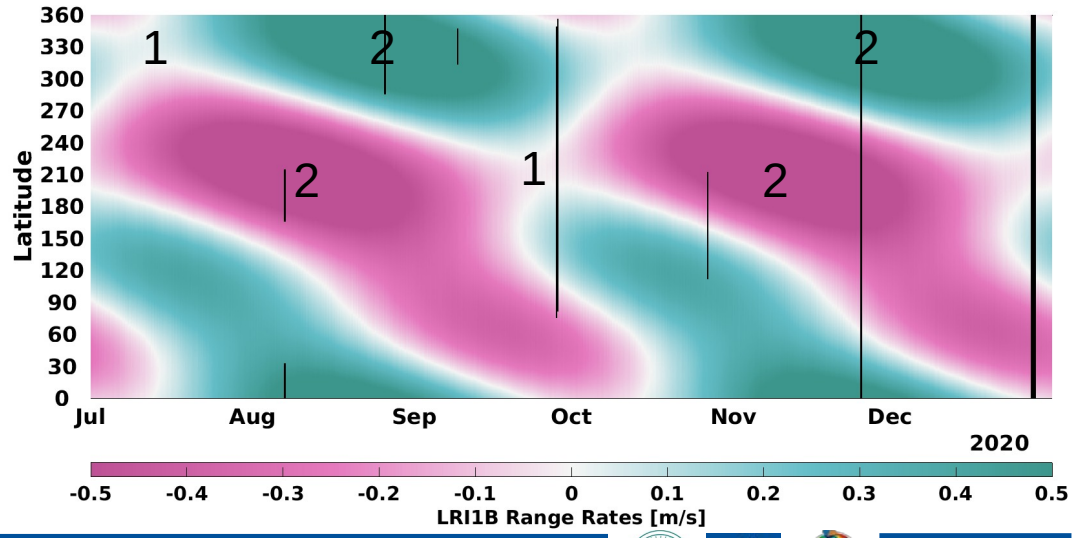


1) Mathias Duwe et al 2024, Residual Patterns in GRACE Follow-On Laser Ranging Interferometry Post-Fit Range Rate Residuals, https://doi.org/10.1016/j.asr.2024.03.035

Residual Patterns already in LRI1B

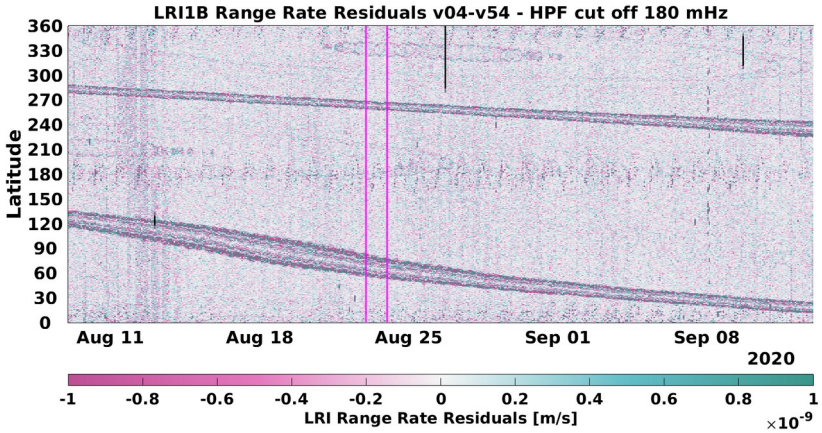
- Comparing LRI1B v04-v54 high-pass filtered biased ranges, range rates or range accl (without light time correction) show the same features.
- Effects occur when range rate gets
  1) close to zero (mesh pattern)
  2) close to max or minimum (elliptical rings)

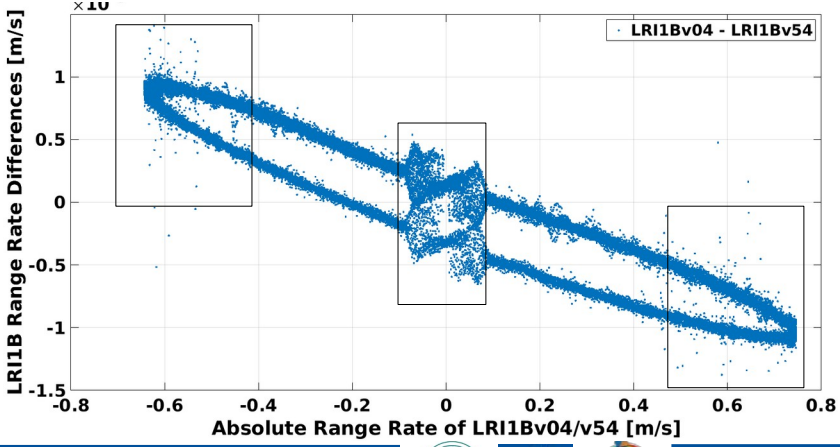




Correlation between Residuals and Range Rates

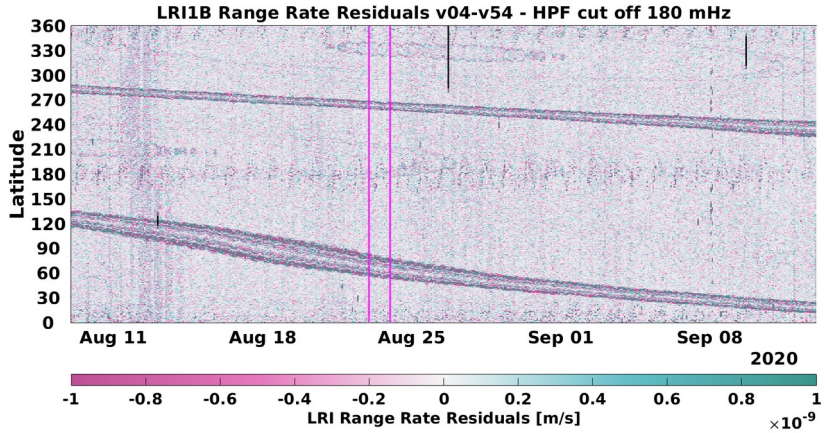
- 2020-08-23 contains zero crossings and elliptical rings
- LRI1B residuals (not filtered) over range rates show:
  - ellipse, due to different scale and time shift
  - clustering around 0 m/s
  - outliers at minimal and maximal range rates

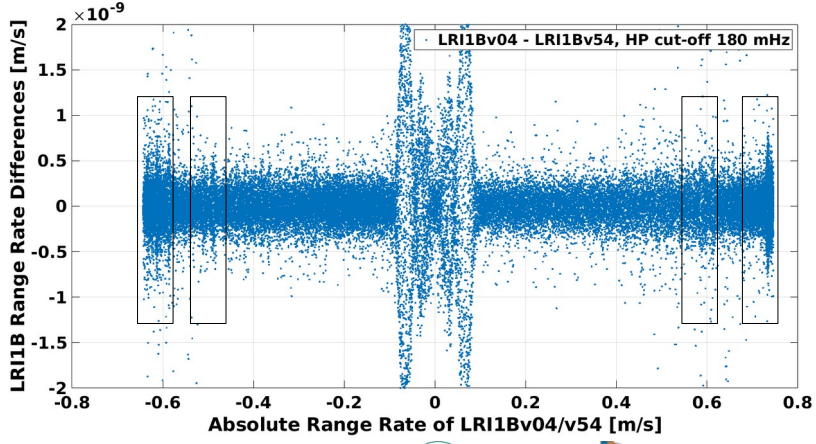




Artifacts at Particular Range Rate Values

- 2020-08-23 contains zero crossings and elliptical rings
- LRI1B residuals (not filtered) over range rates show:
  - ellipse, due to different scale and time shift
  - clustering around 0 m/s
  - outliers at minimal and maximal range rates
- High-pass filtered LRI1B residuals over range rates makes it easier to identify cluster at certain range rates

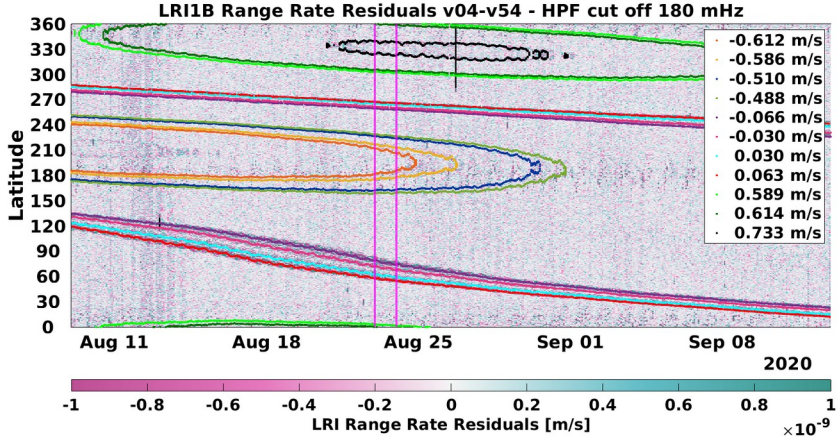


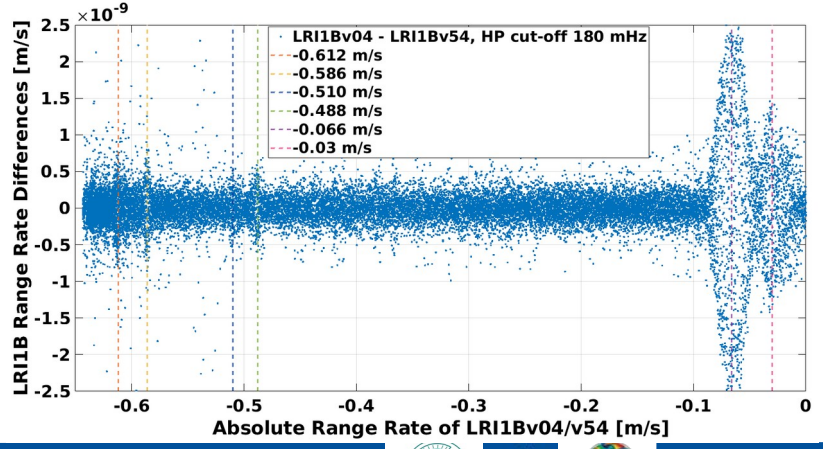


Artifacts at Particular Range Rate Values

- 2020-08-23 contains zero crossings and elliptical rings
- LRI1B residuals (not filtered) over range rates show:
  - ellipse, due to different scale and time shift
  - clustering around 0 m/s
  - outliers at minimal and maximal range rates
- High-pass filtered LRI1B residuals over range rates makes it easier to identify cluster at certain velocities
- Clustering observed at range rates, where the signatures in Argument of Latitude plots appear.

→ Not clear why effect appears in official LRI1B v04





Checking LRI1A v04 data

We performed analysis if v04 LRI1A data might already contain artifacts related to particular absolute range-rate values.

- Our hypotheses were that artifacts might be caused by
  - piston phase quantity, which has lower numerical accuracy than the raw individual phase values (double floating point vs. unsigned integer 64-bit)
  - loss of precision in the time-tag values (rounded to nanosecond in LRI1A)
- Neither hypothesis was supported by the data (some plots are shown in the back-up slides below)

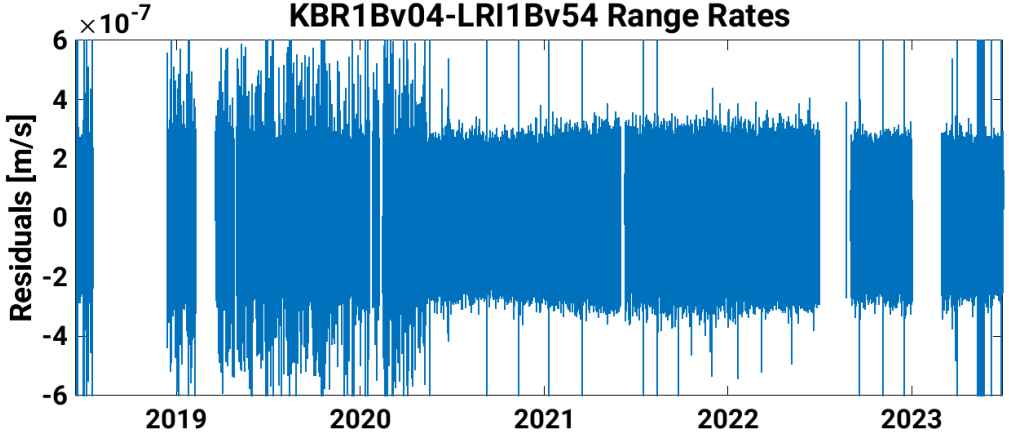
→ v04 LRI1A data seems not to be affected by artifacts at particular range rates

→ artifacts / signatures probably introduced in v04 L1A-> L1B processing

KBR & LRI Residuals in Time Domain

KBR1B v04 – LRI1B v54 Range Rate Residuals are dominated by

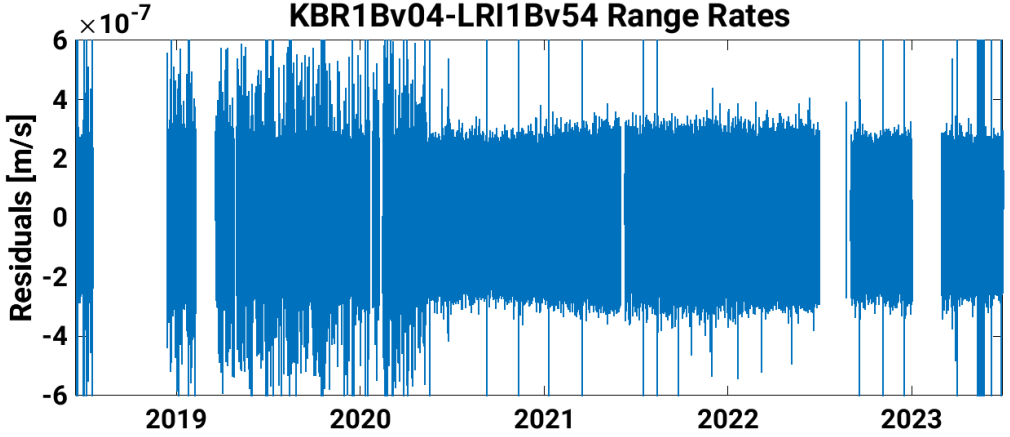
- high frequency noise
  - from KBR phase readout approx. +/-0.3 µm/s
  - 2018 – March 2020 several peaks most likely related to outlier in CLK1B

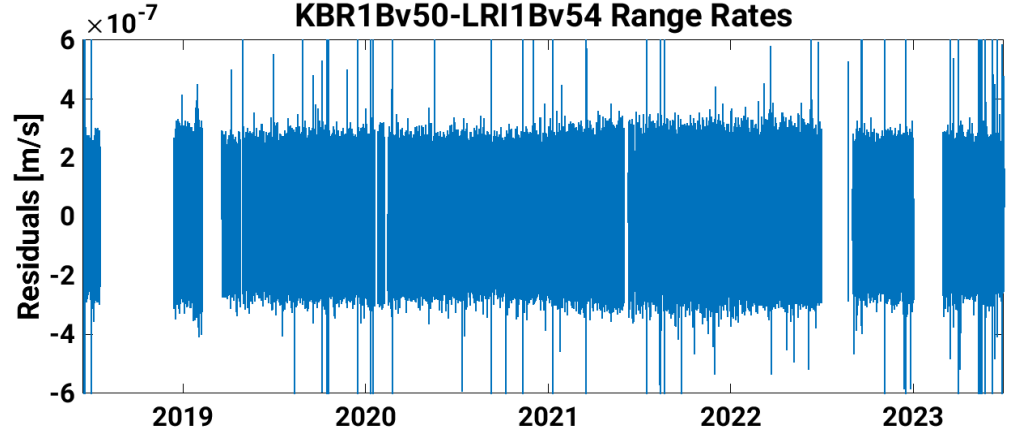


KBR & LRI Residuals in Time Domain

KBR1B v04 – LRI1B v54 Range Rate Residuals are dominated by

- high frequency noise
  - from KBR phase readout approx. +/-0.3 µm/s
  - 2018 – March 2020 several peaks most likely related to outlier in CLK1B



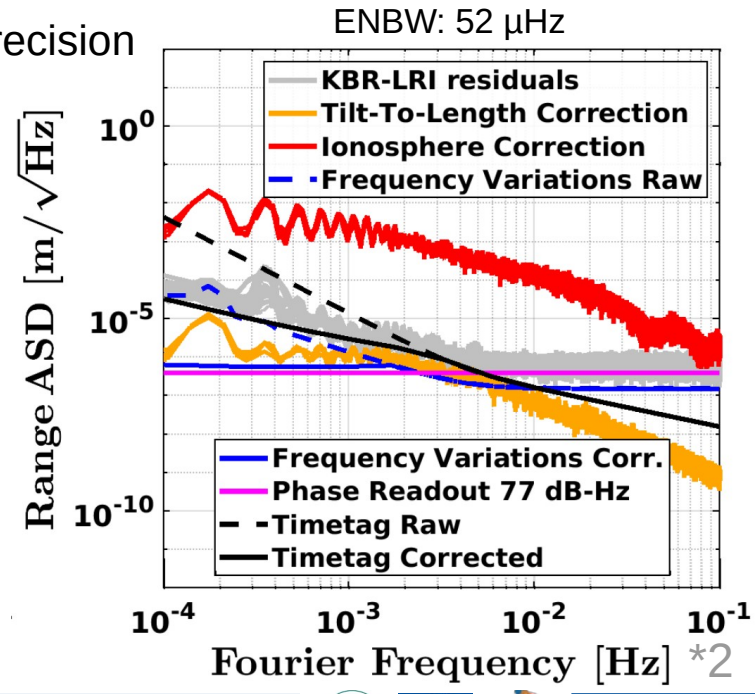


AEI-KBR1B v50 does not show as many outliers as v04 in the first period.

AEI-KBR1B v50 available at
https://doi.org/10.25625/MCTZKS
(Publication in preparation, by Yihao Yan et al.)

KBR & LRI Residuals in Frequency Domain

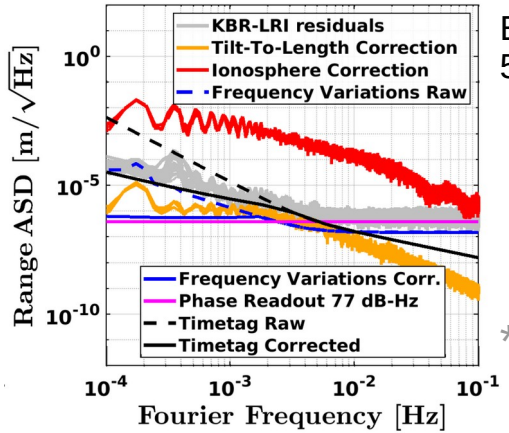
- ASD show KBR-LRI residuals with gray traces for all days in January 2019.
- KBR-LRI residuals seems to be limited at [2]
  - high frequencies: by the KBR phase readout noise
  - low frequencies: by time-tag precision determined by the CLK1B precision



2) V. Müller et al., Comparing GRACE-FO KBR and LRI ranging data with focus on carrier frequency variations, 2022, https://doi.org/10.3390/rs14174335

KBR & LRI Residuals in Frequency Domain

- ASD show KBR-LRI residuals with gray traces for all days in January 2019.
- KBR-LRI residuals seems to be limited at [2]
  - high frequencies: by the KBR phase readout noise
  - low frequencies: by time-tag precision determined by the CLK1B precision

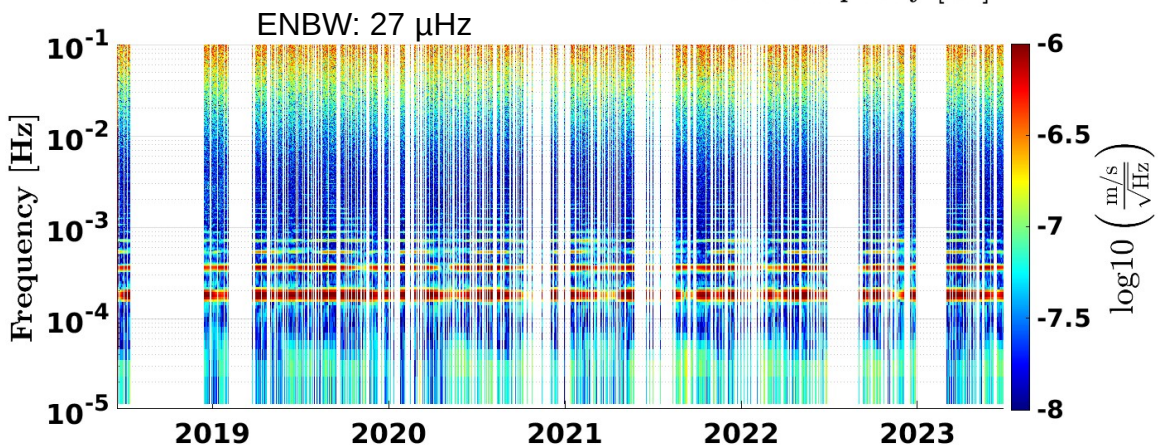


ENBW: 52 µHz

*2

Daily ASD of range rate residuals between KBR1B v04 and LRI1B v54

- seasonal variations in 1/rev...6/rev frequencies, which are correlated to temperature variations which might couple into the KBR system [3]
- 2/rev maximum difference ~5 nm/s rms amplitude (correspond to ~0.013 nm/s^2)
- high frequencies above 1 mHz show no obvious features

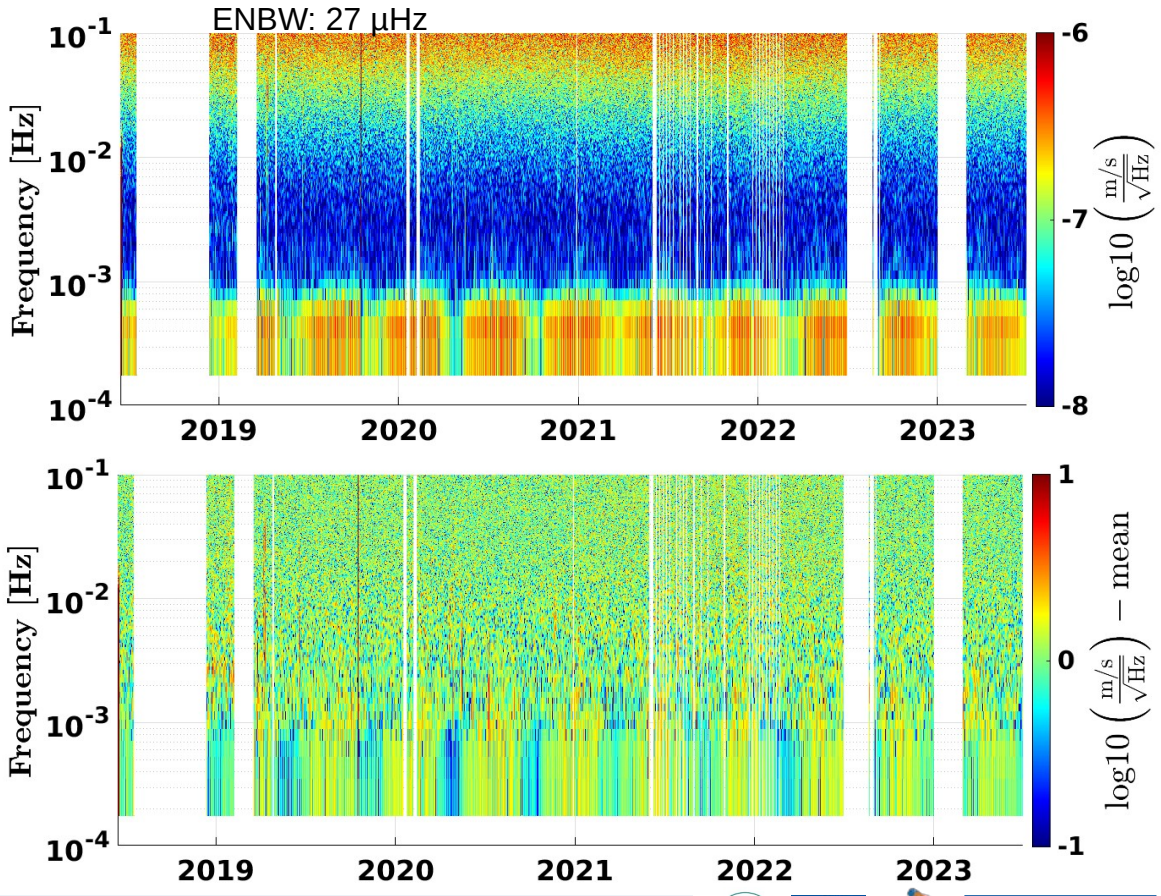


3) M. Misfeldt et al., Scale Factor Determination for the GRACE-Follow On Laser Ranging Interferometer including Thermal Correction, 2022, https://doi.org/10.3390/rs15030570

KBR & LRI Residuals in Frequency Domain

Orbit-wise ASD for finer resolution:
- show seasonal variations at n/rev
- high frequencies above 1 mHz show no special patterns

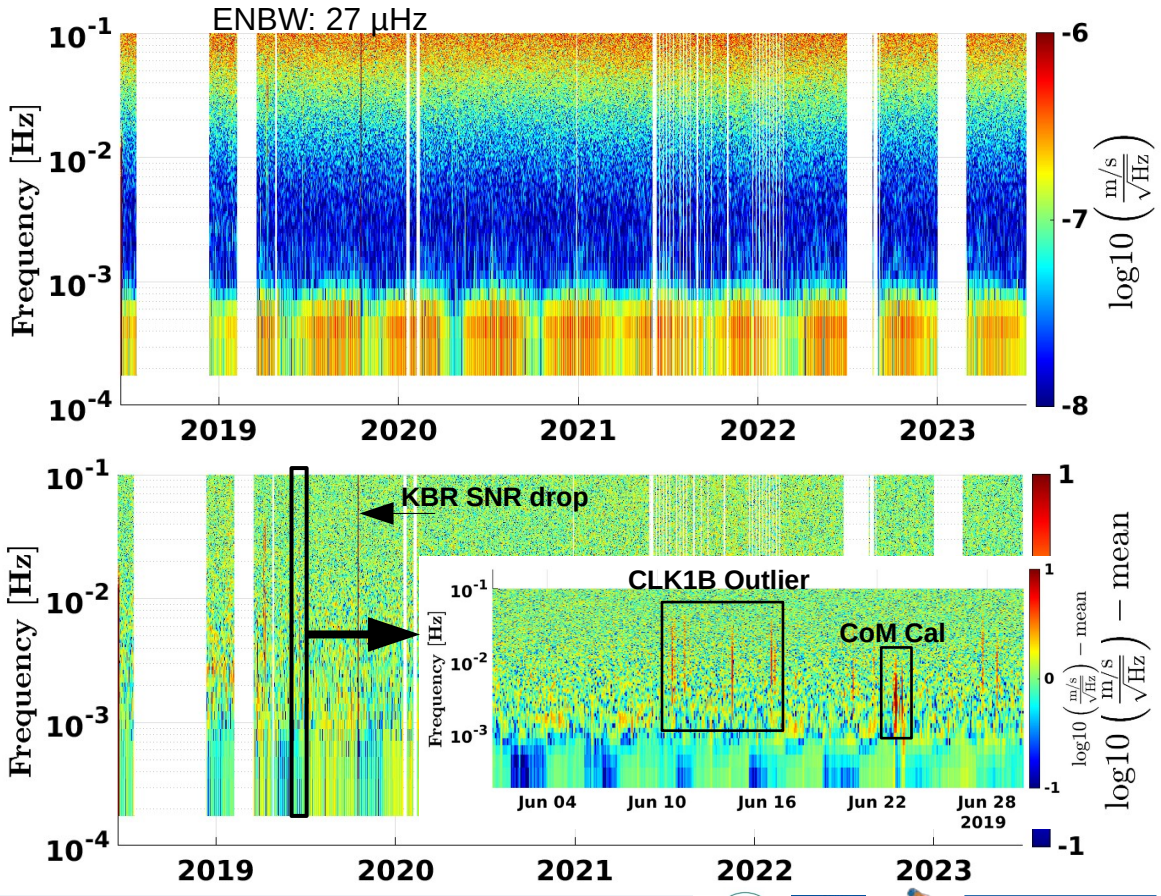
Orbit-wise ASD minus mean value of each frequency bin over complete time span:
- in general noise in residuals relatively similar for whole time span
- few disturbances are visible at:
  - satellite maneuvers like CoM calibrations or thruster plateau tests
  - 2019-10-16/17 with KBR SNR drop,
  - e.g. 2019-05-09, 2019-06-10/11 caused by CLK1B outliers



KBR & LRI Residuals in Frequency Domain

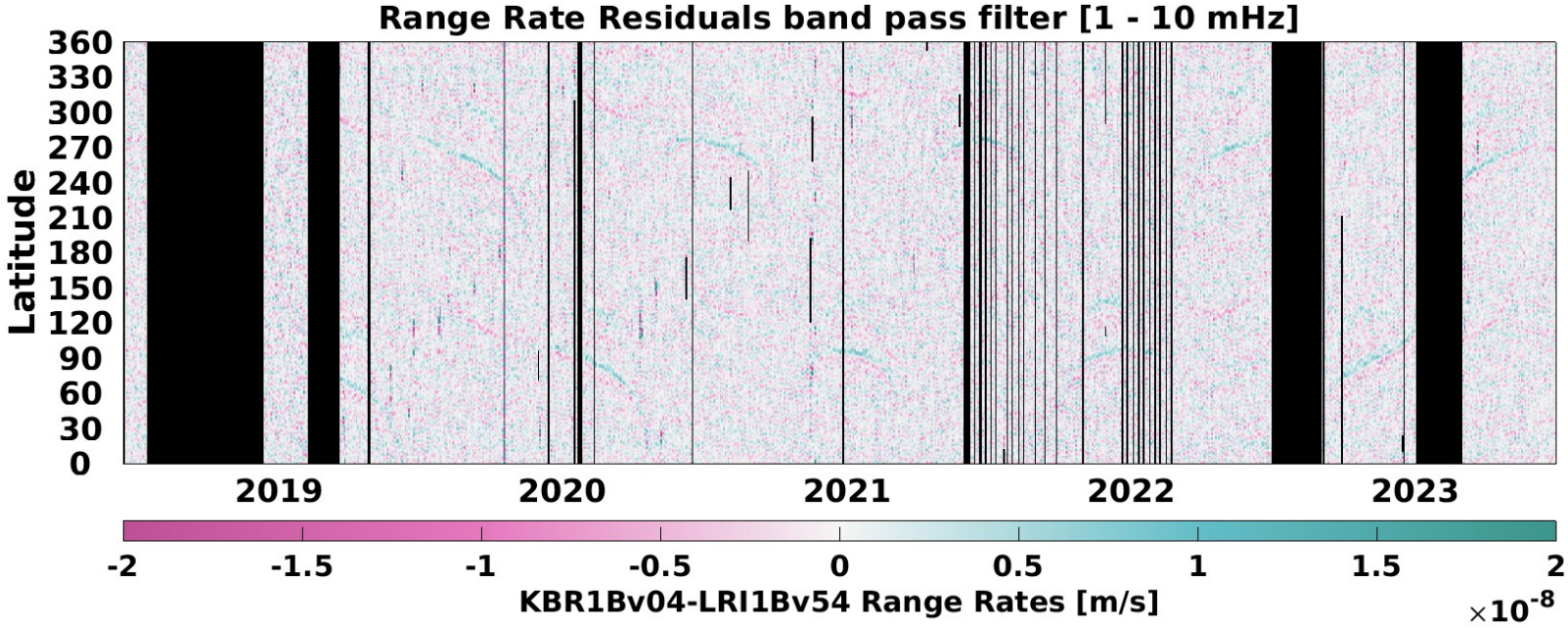
Orbit-wise ASD for finer resolution:
- show seasonal variations at n/rev
- high frequencies above 1 mHz show no special patterns

Orbit-wise ASD minus mean value of each frequency bin over complete time span:
- in general noise in residuals relatively similar for whole time span
- few disturbances are visible at:
  - satellite maneuvers like CoM calibrations or thruster plateau tests
  - 2019-10-16/17 with KBR SNR drop,
  - e.g. 2019-05-09, 2019-06-10/11 caused by CLK1B outliers



KBR & LRI Residuals in Geographic Domain

- Frequencies above 10 mHz dominated by KBR noise
- Here frequency band between 1 mHz and 10 mHz
- shadow transitions are slightly visible
- Otherwise no special differences observable in geographic domain



Conclusion

LRI1B v04 – v54 artifacts related to particular range rate values

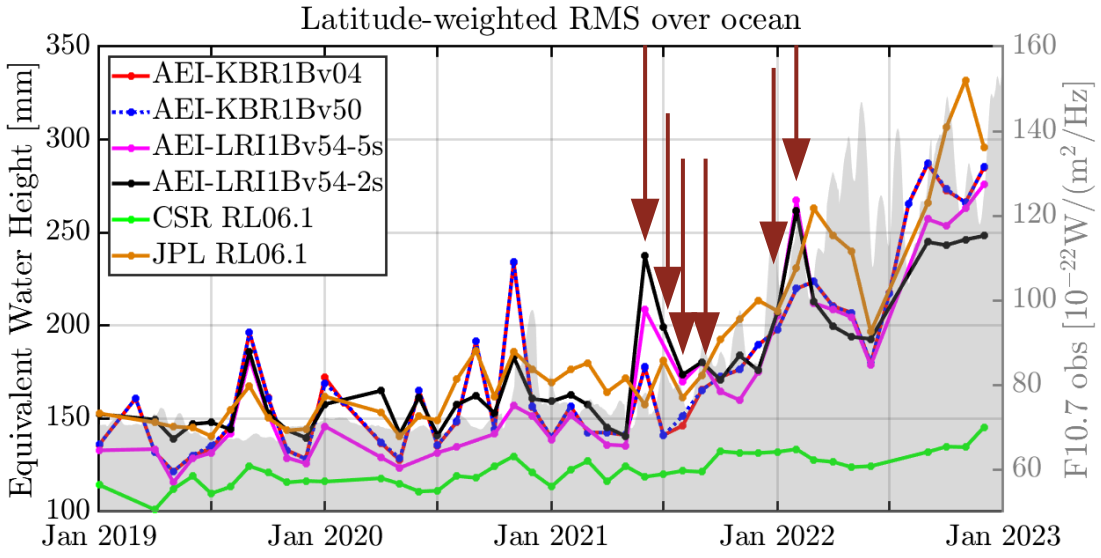
- LRI1B v04 exhibits some artifacts, which are not in AEI-LRI1B v50 & v54
- No evidence found that LRI1A v04 is affected
- Effects couple during L1A→ L1B processing

KBR1B v04 – LRI1B v54 Comparison

- KBR1B v04 - LRI1B v54 residuals
  - are dominated by the KBR noise level above 1 mHz
  - show shadow transitions between 1 - 10 mHz in geographic domain
  - show seasonal variations in differences at 1/rev...6/rev tone-frequencies
- Largest differences, e.g. at 2/rev, reach rms amplitudes of ~0.5 nm/s (~2.6 um or ~0.013 nm/s^2), which might cause differences in the gravity field recovery
- However, we assume that monthly gravity fields from both ranging instruments should still result in (at least) similar values for the ocean RMS.
- AEI provides a LRI1B dataset with 0.2 Hz sampling and KBR CRN filter parameters, to simplify comparison between LRI and KBR and exclude that CRN filter or data rate has an impact..

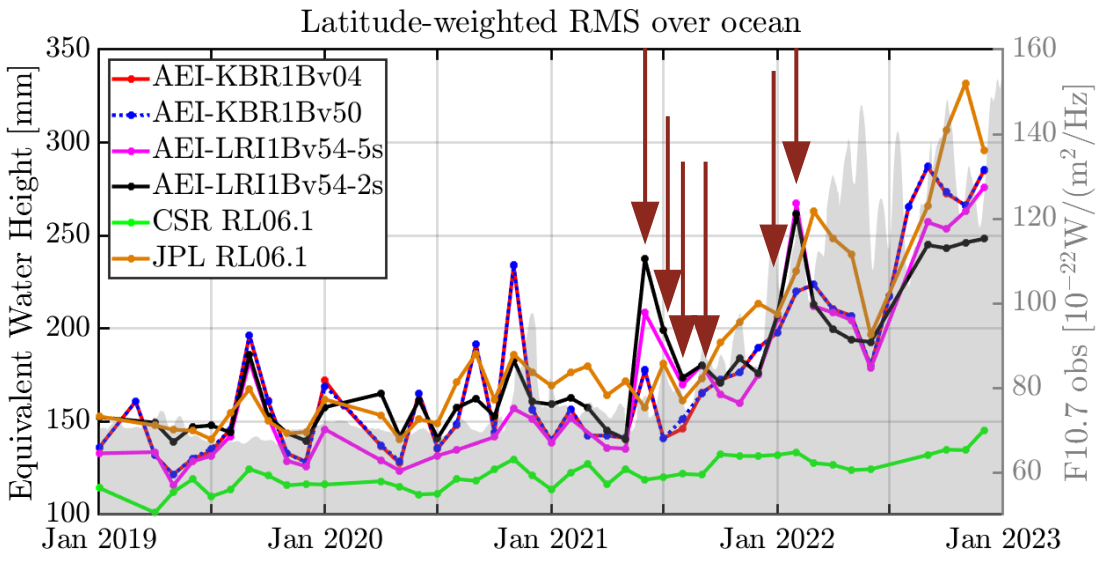
Outlook

- Processing the 0.2 Hz AEI-LRI1Bv54 dataset with GSOFT, yield lower or equal ocean RMS values for LRI (pink curve), in comparison to KBR (red & blue curve)
- Exceptions are month where less LRI data was available, e.g. due to NADIR-pointing (June-September 2021 January & February 2022)



Outlook

- Processing the 0.2 Hz AEI-LRI1Bv54 dataset with GSOFT, yield lower or equal ocean RMS values for LRI (pink curve), in comparison to KBR (red & blue curve)
- Exceptions are month where less LRI data was available, e.g. due to NADIR-pointing (June-September 2021 January & February 2022)
- Next Steps:
  We need to figure out,
  how to achieve an optimal
  LRI Level 2 data processing,
  and why the sampling rate
  has an impact on the solutions.



References

[1] Mathias Duwe et al 2024, Residual Patterns in GRACE Follow-On Laser Ranging Interferometry Post-Fit Range Rate Residuals, https://doi.org/10.1016/j.asr.2024.03.035

[2] Vitali Müller et al, 2022, Comparing GRACE-FO KBR and LRI ranging data with focus on carrier frequency variations, https://doi.org/10.3390/rs14174335

[3] Malte Misfeldt et al. 2022, Scale Factor Determination for the GRACE-Follow On Laser Ranging Interferometer including Thermal Correction, https://doi.org/10.3390/rs15030570

Other related references for AEI LRI1B processing:

Laura Müller, 2021, Generation of Level 1 Data Products and Validating the Correctness of Currently Available Release 04 Data for the GRACE Follow-On Laser Ranging Interferometer, Master's thesis, DOI:http://doi.org/10.15488

Yihao Yan et al, 2020, Revisiting the Light Time Correction in Gravimetric Missions Like GRACE and GRACE Follow-On, https://doi.org/10.1007/s00190-021-01498-5

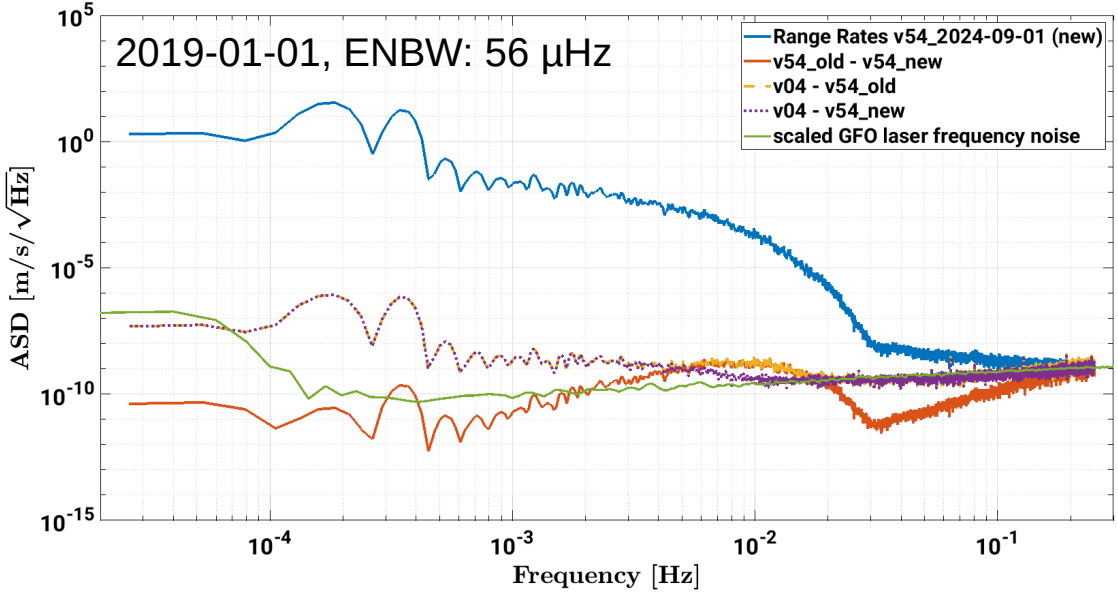
Henry Wegener, 2020, Tilt-to-Length Coupling in the GRACE Follow-On Laser Ranging Interferometer, https://doi.org/10.2514/1.A34790

AEI-LRI1B: https://www.aei.mpg.de/grace-fo-ranging-datasets
AEI-KBR1B: https://doi.org/10.25625/MCTZKS

Back Up Slides

LRI1B v54 2024-09-01 Improvement

- Previous method of computing time derivatives on 0.5 Hz rate inserted noise around 10 mHz
- Computing derivatives on 10 Hz rate, with numerical approach or CRN filter, lowers the bump at 10 mHz by at least a factor of 2



Checking LRI1A v04 for certain range rate patterns

- LRI1A provides
  1) raw phase measurements from four photo-diode channels as uint64 (2x uint32)
  2) mean phase (piston phase) with double precision → further processed to L1B biased range

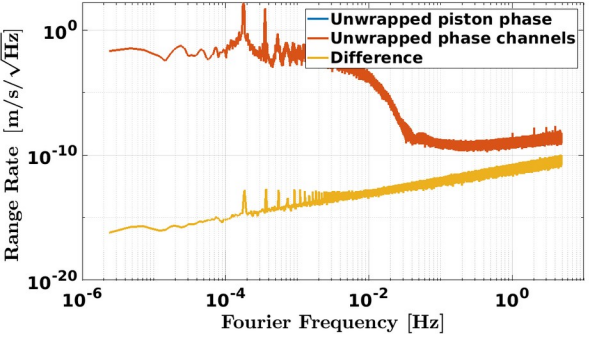
LRI1A v04 Format

				Piston Phase	Channel 0		Channel 1		Channel 2		Channel 3	
183	# End of YAML header											
184	599572800	64095949	C 0000000111111111 00000000	78561638205.90274	3068813992	1795771311	3068813992	1795477384	3068813992	1795477262	3068813992	1795771172
185	599572800	167572770	C 0000000111111111 00000000	78562759128.66217	3068857778	1990287169	3068857778	1989996250	3068857778	1989996235	3068857778	1990287307
186	599572800	271049591	C 0000000111111111 00000000	78563880063.02751	3068901564	4131954641	3068901564	4131664004	3068901564	4131664035	3068901564	4131954687
187	599572800	374526412	C 0000000111111111 00000000	78565001009.00334	3068945351	3926574460	3068945351	3926283313	3068945351	3926283273	3068945351	3926574472
188	599572800	478003234	C 0000000111111111 00000000	78566121966.58719	3068989139	1373725692	3068989139	1373432695	3068989139	1373432765	3068989139	1373725633
189	599572800	581480055	C 0000000111111111 00000000	78567242935.77693	3069032927	768026978	3069032927	767737480	3069032927	767737528	3069032927	768026776
190	599572800	684956876	C 0000000111111111 00000000	78568363916.57001	3069076715	2109044725	3069076715	2108751859	3069076715	2108751716	3069076715	2109044873
191	599572800	788433697	C 0000000111111111 00000000	78569484908.96179	3069120504	1101032145	3069120504	1100739759	3069120504	1100739780	3069120504	1101032229
192	599572800	891910518	C 0000000111111111 00000000	78570605912.95645	3069164293	2039659136	3069164293	2039365509	3069164293	2039365497	3069164293	2039659176
193	599572800	995387340	C 0000000111111111 00000000	78571726928.54474	3069208083	628409030	3069208083	628112846	3069208083	628112884	3069208083	628408899

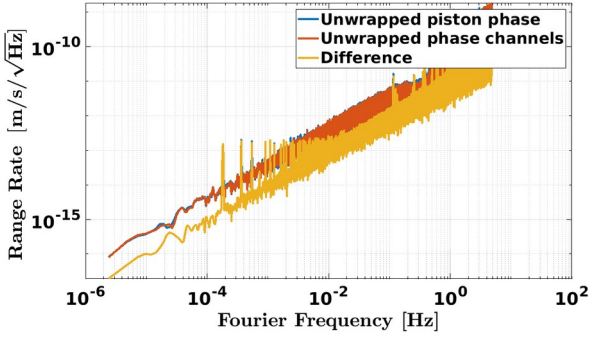
Checking LRI1A v04 for certain range rate patterns

- LRI1A provides
  1) raw phase measurements from four photo-diode channels as uint64 (2x uint32)
  2) mean phase (piston phase) with double precision → further processed to L1B
- We unwrapped phases of 1) & 2) and plotted their differences
- Piston Phase is less precise, but differences smaller than 1e-10 m/s and also range rate correlated patterns (like mesh-pattern) cannot be observed
  → LRI1A v04 piston phase most likely not affecte

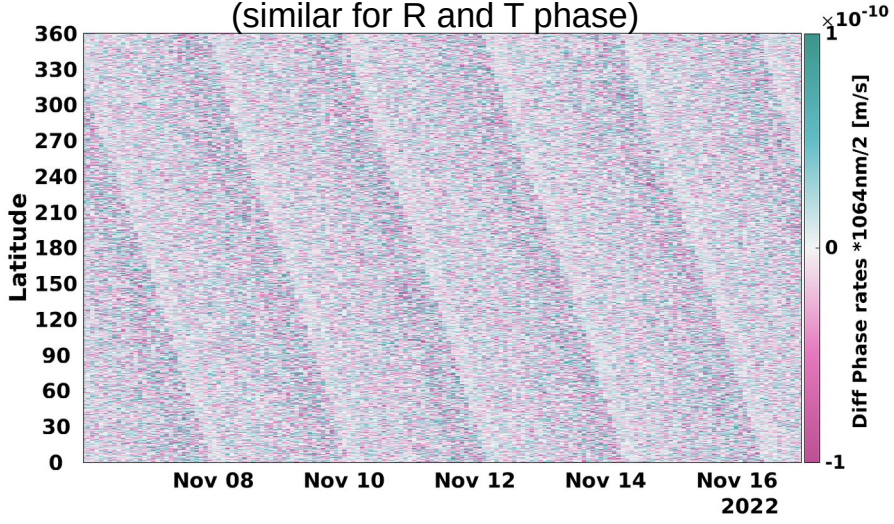
Reference (R)
Phase Rate *1064nm/2



Transponder (T)
Phase Rate *1064nm/2



(similar for R and T phase)



[Data for ArgLat plot not high-pass filtered.]

Checking LRI1A v04 for certain range rate patterns

- LRI1A v04 time-tags are rounded to nanoseconds,
  while LRP provides time-tags in femtosecond resolution

LRI1A v04 Format

```
87      - rcv_time:
88          comment: 1st column
89          coverage_content_type: referenceInformation
90          long_name: Seconds past 12:00:00 noon of January 1, 2000 in LRI Time
91          units: seconds
92      - rcvtime_frac:
93          comment: 2nd column
94          coverage_content_type: referenceInformation
95          long_name: Fractional portion of time tag
96          units: nanoseconds
97          valid_range: 0, 999999999
```

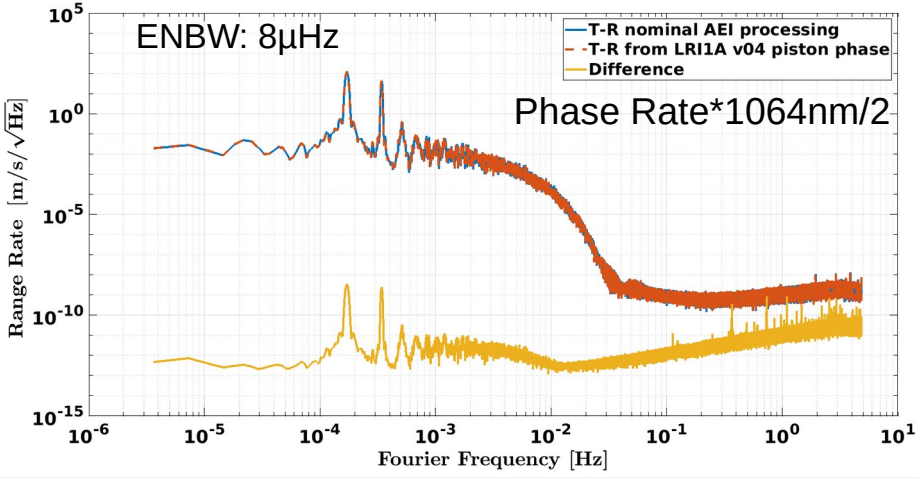
```
183 # End of YAML header
184 599572800 64095949 C  0000000111111111  00000000    78561638205.90274  3068813992  1795771311  3068813992  1795477384  3068813992  1795477262  3068813992  1795771172
185 599572800 167572770 C  0000000111111111  00000000    78562759128.66217  3068857778  1990287169  3068857778  1989996250  3068857778  1989996235  3068857778  1990287307
186 599572800 271049591 C  0000000111111111  00000000    78563880063.02751  3068901564  4131954641  3068901564  4131664004  3068901564  4131664035  3068901564  4131954687
187 599572800 374526412 C  0000000111111111  00000000    78565001009.00334  3068945351  3926574460  3068945351  3926283313  3068945351  3926283273  3068945351  3926574472
188 599572800 478003234 C  0000000111111111  00000000    78566121966.58719  3068989139  1373725692  3068989139  1373432695  3068989139  1373432765  3068989139  1373725633
189 599572800 581480055 C  0000000111111111  00000000    78567242935.77693  3069032927  768026978   3069032927  767737480   3069032927  767737528   3069032927  768026776
190 599572800 684956876 C  0000000111111111  00000000    78568363916.57001  3069076715  2109044725  3069076715  2108751859  3069076715  2108751716  3069076715  2109044873
191 599572800 788433697 C  0000000111111111  00000000    78569484908.96179  3069120504  1101032145  3069120504  1100739759  3069120504  1100739780  3069120504  1101032229
192 599572800 891910518 C  0000000111111111  00000000    78570605912.95645  3069164293  2039659136  3069164293  2039365509  3069164293  2039365497  3069164293  2039659176
193 599572800 995387340 C  0000000111111111  00000000    78571726928.54474  3069208083  628409030   3069208083  628112846   3069208083  628112884   3069208083  628408899
```

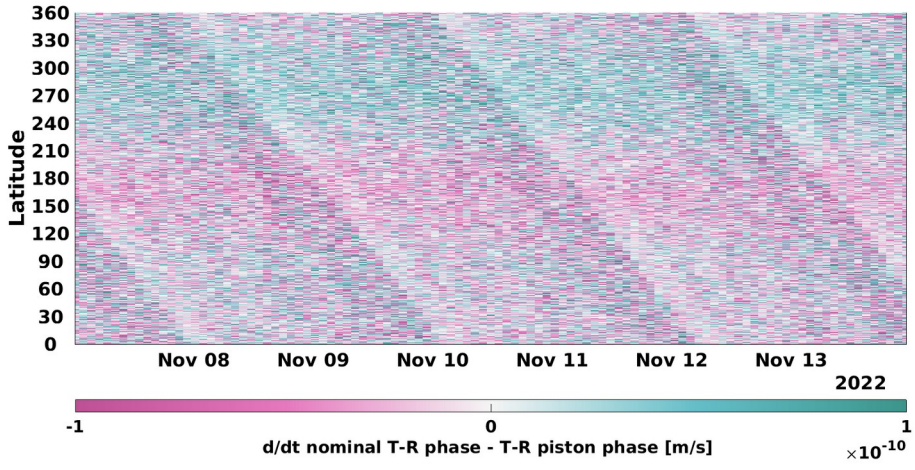
GF1 LRP Time-tag example:
Int: 599572800 GrGps sec
Frac: 2477693 clockticks
Clockrate: 38656000 Hz

rcvtime_frac = clockticks / clockrate *1e9
= 64095948.8824503 nanosec

Checking LRI1A v04 for certain range rate patterns

- LRI1A v04 time-tags are rounded to nanoseconds,
  while LRP provides time-tags in femtosecond resolution
- We computed the LRI phase (transponder-reference phase)
  - from LRI1A v04 piston phase with AEI algorithm
  - from LRI raw phase measurements with AEI algorithm
  After interpolating both sets on the same time-grid, and comparing their difference
  they do not show the signatures (mesh-patterns or elliptic rings)
- LRI1Av04 time-tags are also not causing the signatures like mesh-patterns or elliptic rings
  → LRI1A v04 most likely not affected, signatures couple during L1A→ L1B v04 processing





[Data for ArgLat plot not high-pass filtered.]