On the investigation of post-fit residuals of GRACE(FO)

Mathias Frye (formerly known as Mathias Duwe)

Igor Koch

Jakob Flury

Content

- Processing scheme and estimation of post-fit residuals as side product
- Investigations of high frequency band (with LRI)
- Residual Ocean Tidal signal (with KBR)
- Conclusion

Processing

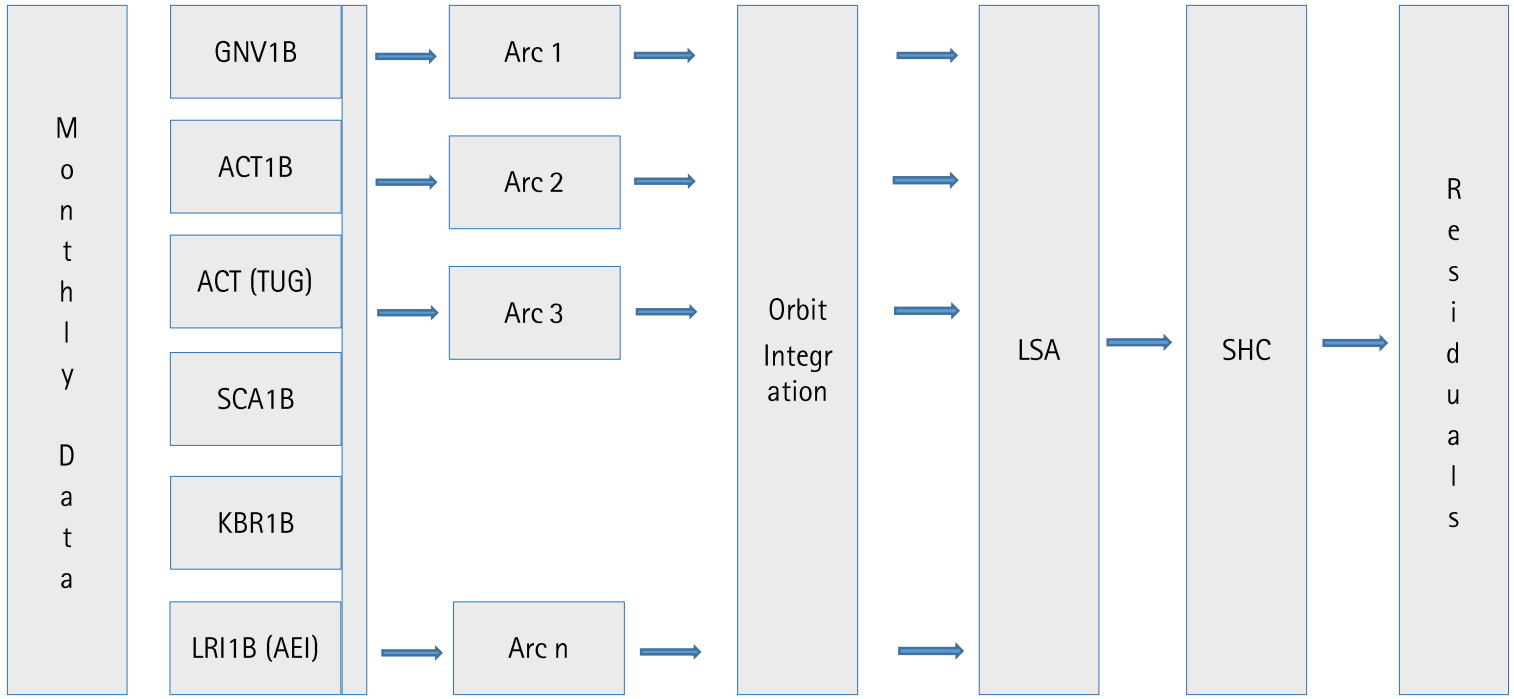


Fig. 1: Processing scheme

- Division of monthly data into smaller batches (Arc)
- For each Arc:
  - Satellite orbit modeling
  - Acceleration modeling
  - State propagation
- Accumulation and Least Squares Adjustment (LSA) to obtain Spherical Harmonic Coefficients (SHC)

Gravity Field Solutions

- A total of 20+ years of KBR gravity fields
- Approx. 4 years of LRI (and combined) gravity fields
- Series shows a good quality among the analysis centers

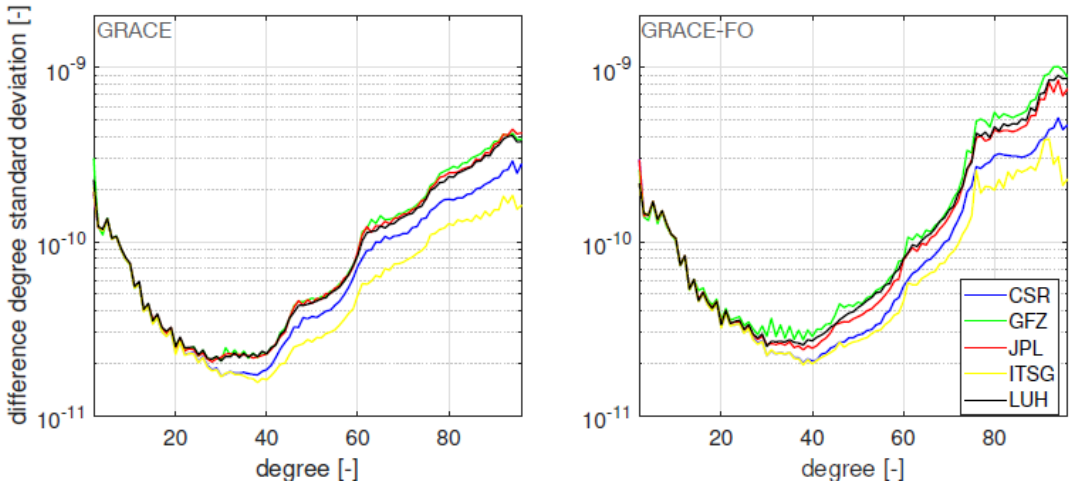


Fig. 2: KBR gravity field solutions, left: GRACE error degree standard deviation, right: GRACE-FO error degree standard deviation

Post-Fit Residuals

- Estimation of post-fit residuals after the estimation of the SHC:
  - $\hat{e} = A\,\Delta\hat{x} - \Delta\hat{l}$
    - A – Design Matrix,
    - $\Delta\hat{x}$ – estimated SHC
    - $\Delta\hat{l}$ – (reduced) observation vector
    - $\hat{e}$ – post-fit residuals

- Visualization as Time - Argument of Latitude (TAL) diagram

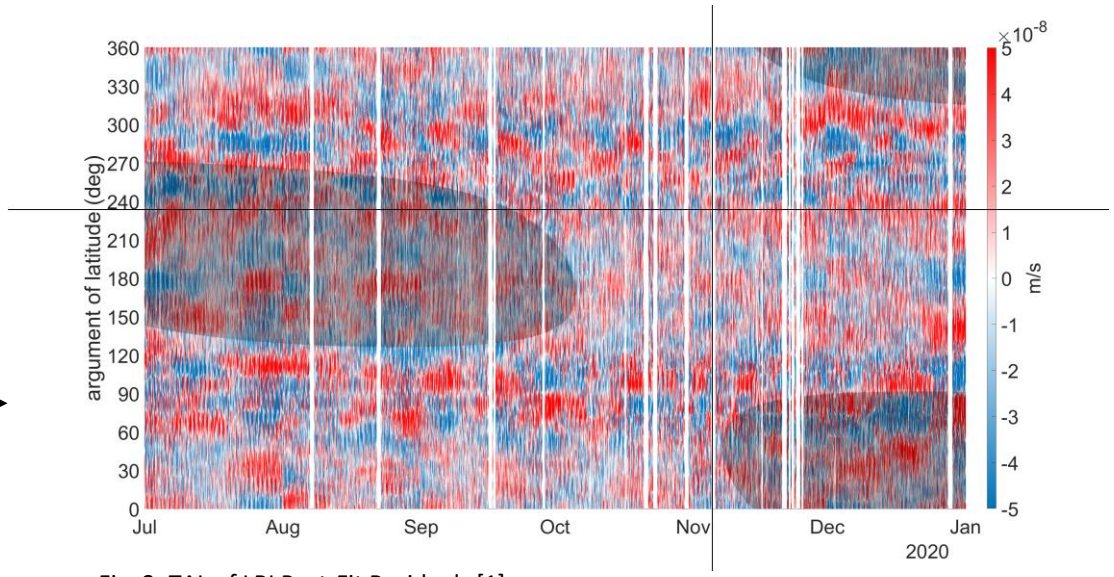


Fig. 3: TAL of LRI Post-Fit Residuals [1]

Filtering Techniques

- Full spectrum Post-Fit residuals show (dominant) high frequent mass change signal
- Different filtering techniques can be used to analyze specific frequency bands

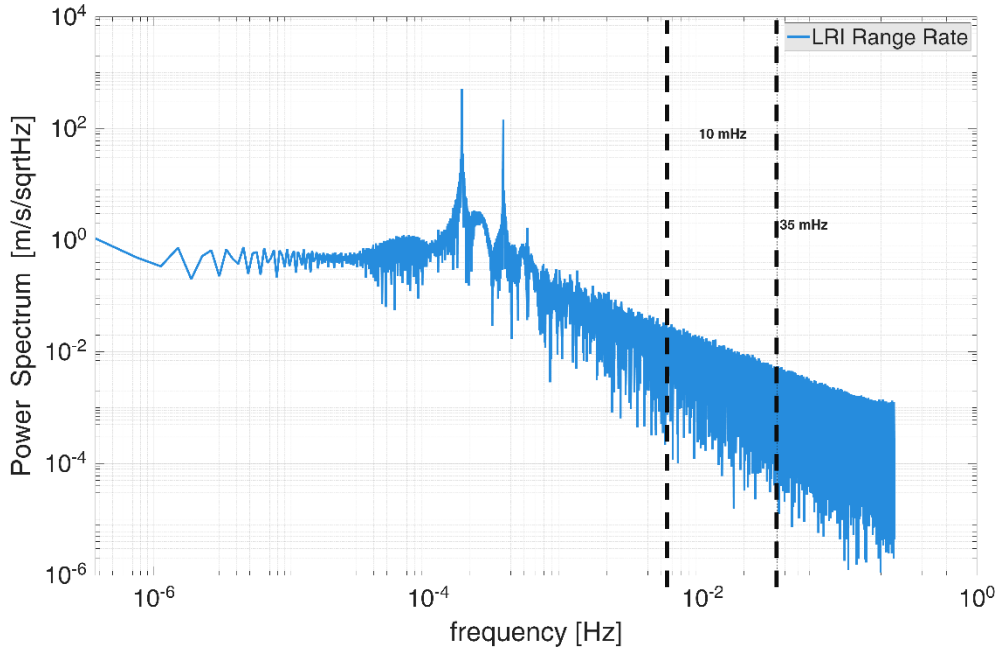


Fig. 4: Power Spectral Density of LRI Range Rate observations

Pre-Fit vs. Post-Fit

- Most of the signal is getting absorbed by SHC

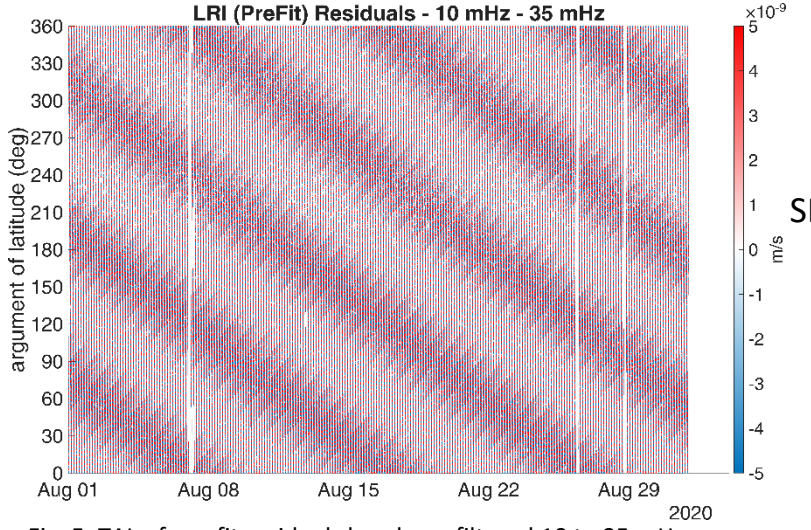


Fig. 5: TAL of pre-fit residuals bandpass filtered 10 to 35 mHz

SHC (+ ACC parameters)

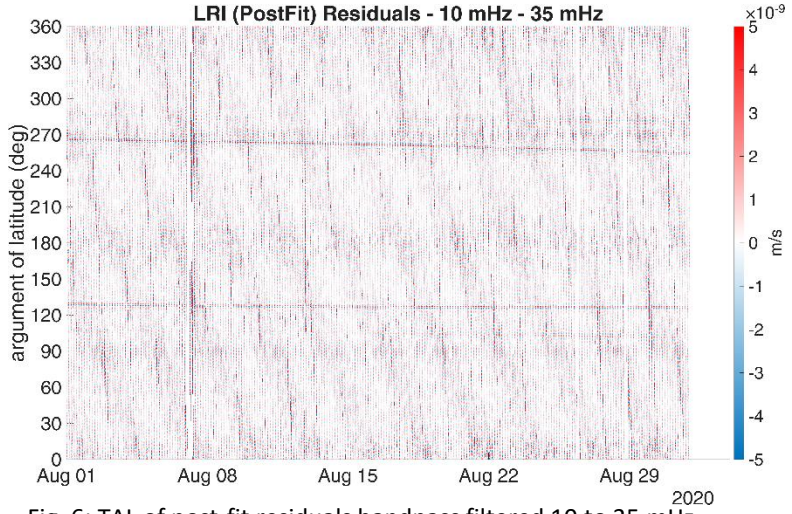
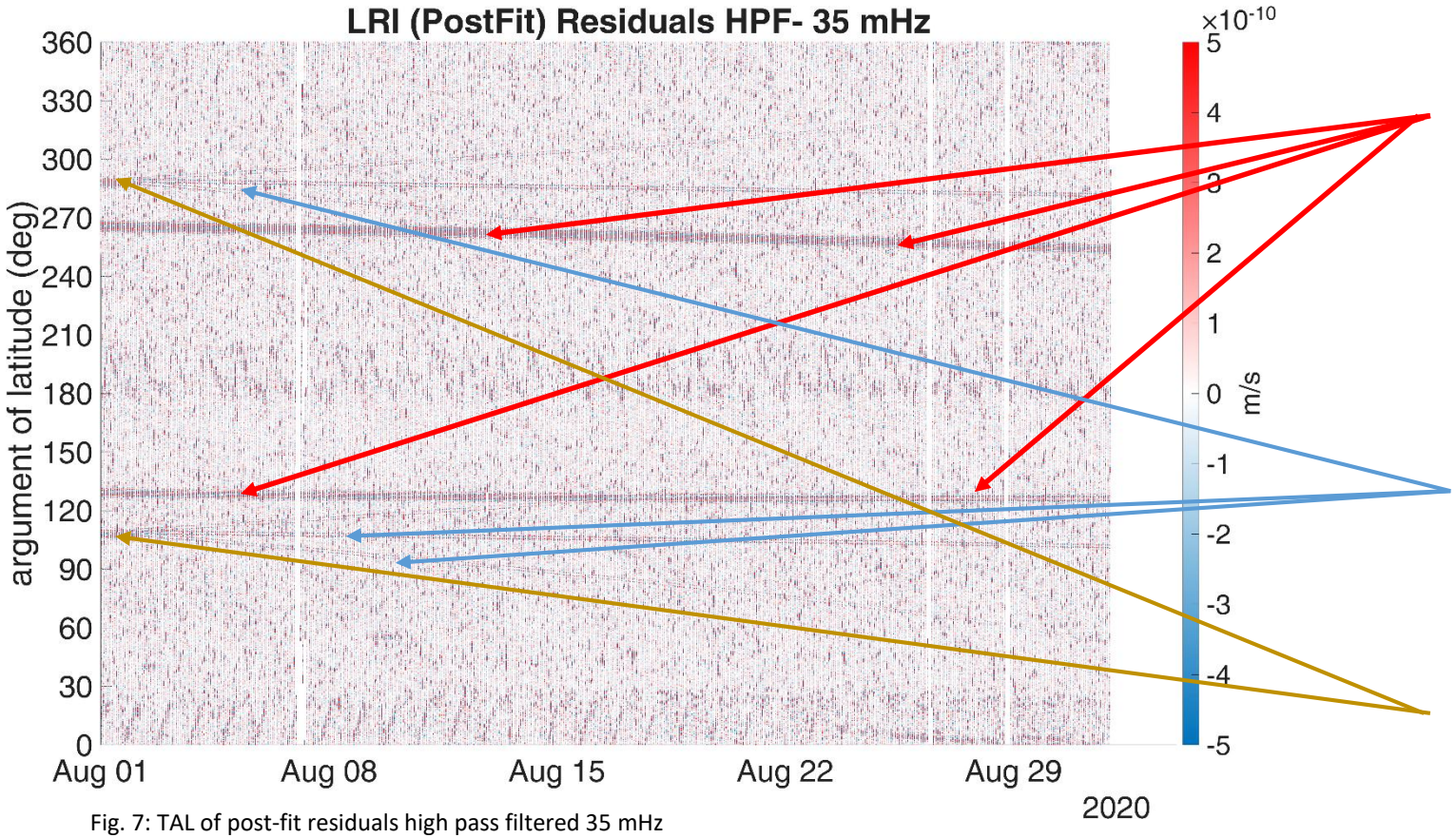


Fig. 6: TAL of post-fit residuals bandpass filtered 10 to 35 mHz

- Some signal is still left in the (Post-Fit) Residuals

What is left in the (Post-Fit) Residuals (high frequency)?



- Shadow entry/exit
- Panel effects
- LRI „blindings“

Fig. 7: TAL of post-fit residuals high pass filtered 35 mHz

What is left in the (Post-Fit) Residuals (high frequency)?

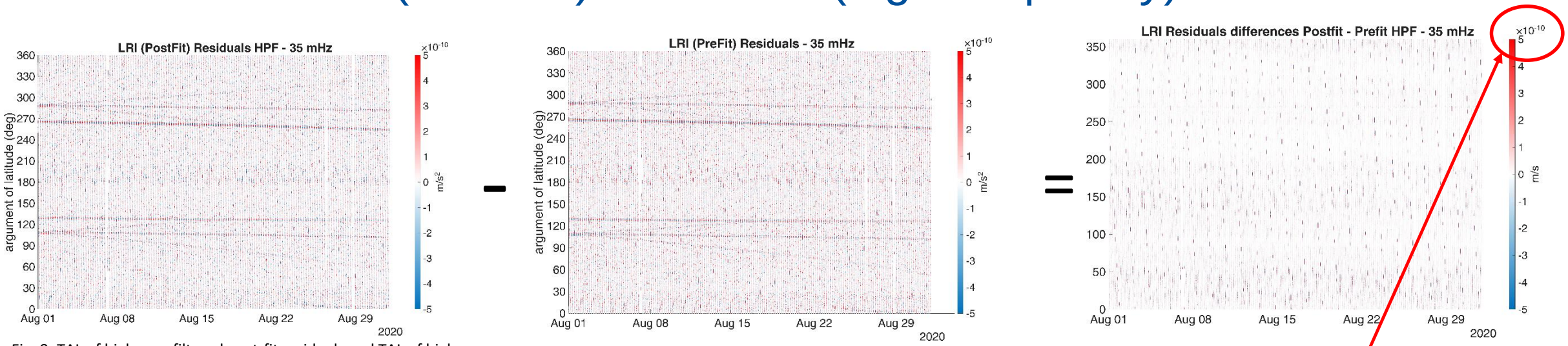


Fig. 8: TAL of high pass filtered post-fit residuals and TAL of high pass filtered pre-fit residuals, as well as their difference

- (very) high frequent signal is still left –> SHC‘s dont absorb these signals

- Less than LRI accuracy -> can be considered as noise

Residual Ocean Tide Signal

- 1. Low-pass filtering of (KBR) Post-Fit Residuals
  - suppress K-band system noise
- 2. Numerical differentiation
  - for better signal localization
- 3. Assigning to a global grid
- 4. Lomb-Scargle Periodogram

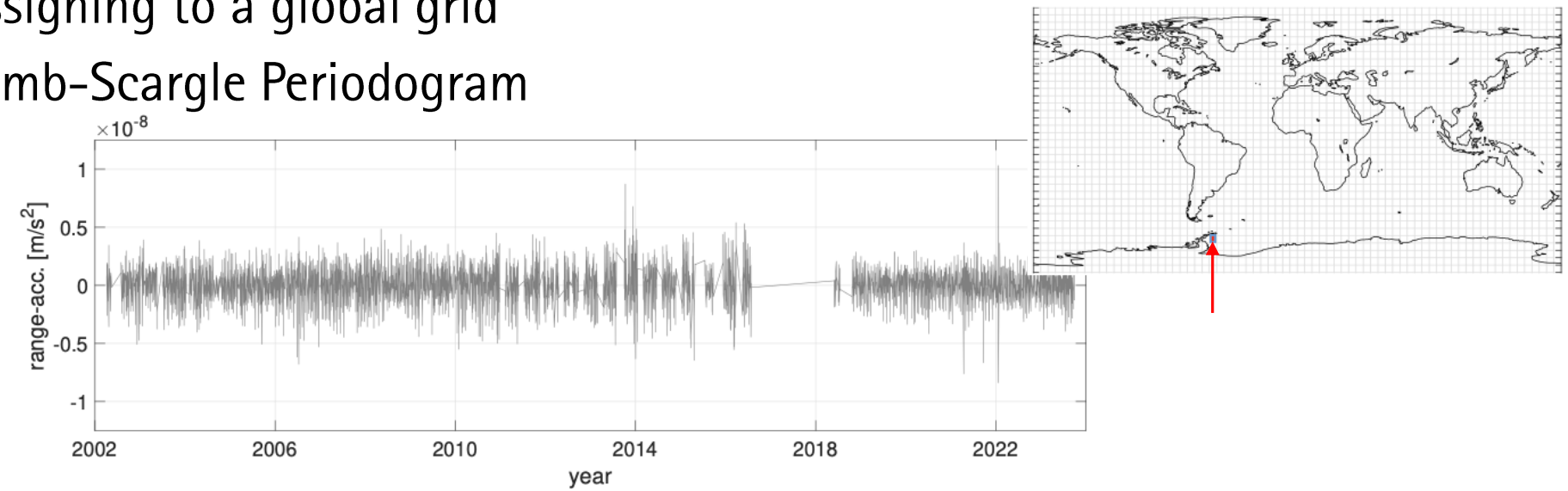
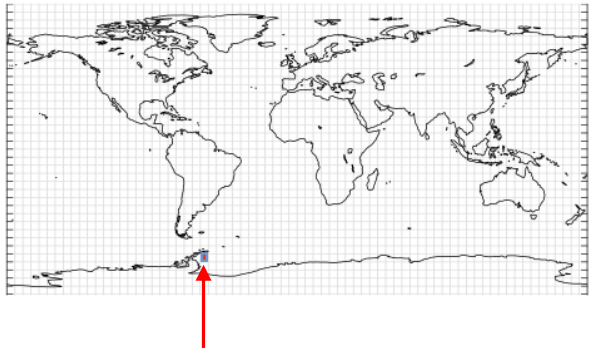


Fig. 9: Time series of a grid cell with assigned post-fit residuals [2]

Exemplary Periodogram

- Periodogram contains redundant peaks
- But also peaks from higher-frequency bands that are not resolved



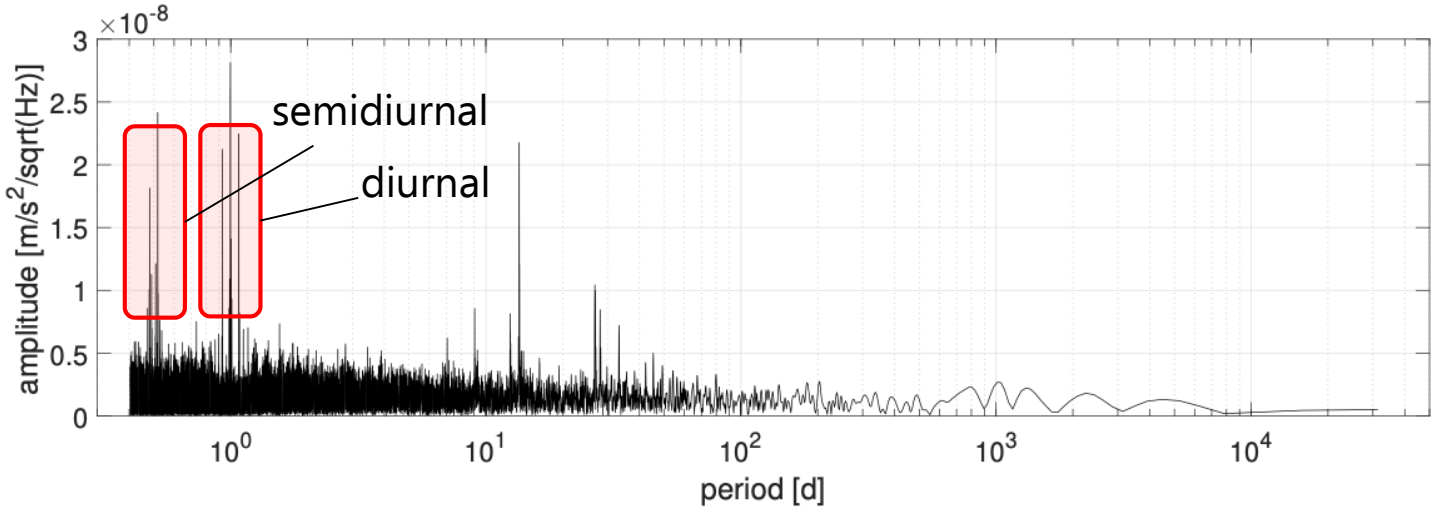
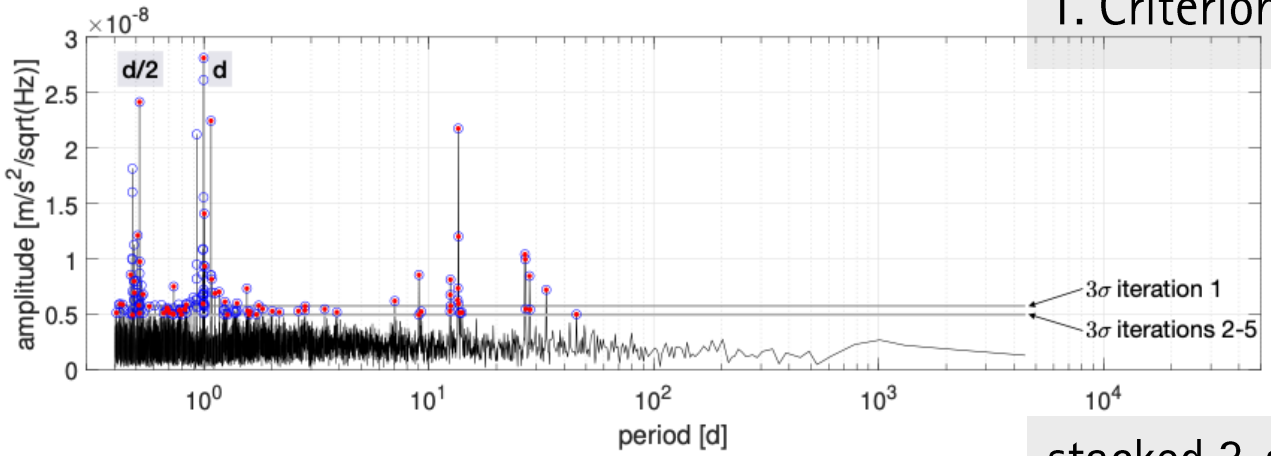


Fig. 10: Lomb-Scargle periodogram of a grid cell with assigned post-fit residuals [2]

Extracting Important Periods

1. Criterion: 3-sigma



stacked 3-sigma plot

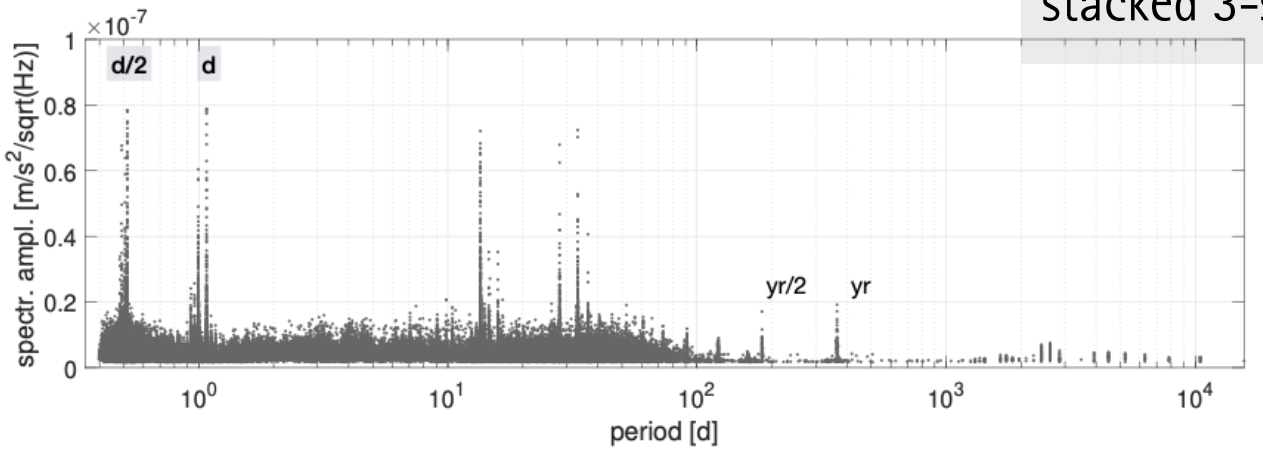


Fig. 11: Lomb-Scargle periodogram of a grid cell with assigned post-fit residuals, identification of significant peaks [2]

Diurnal Band

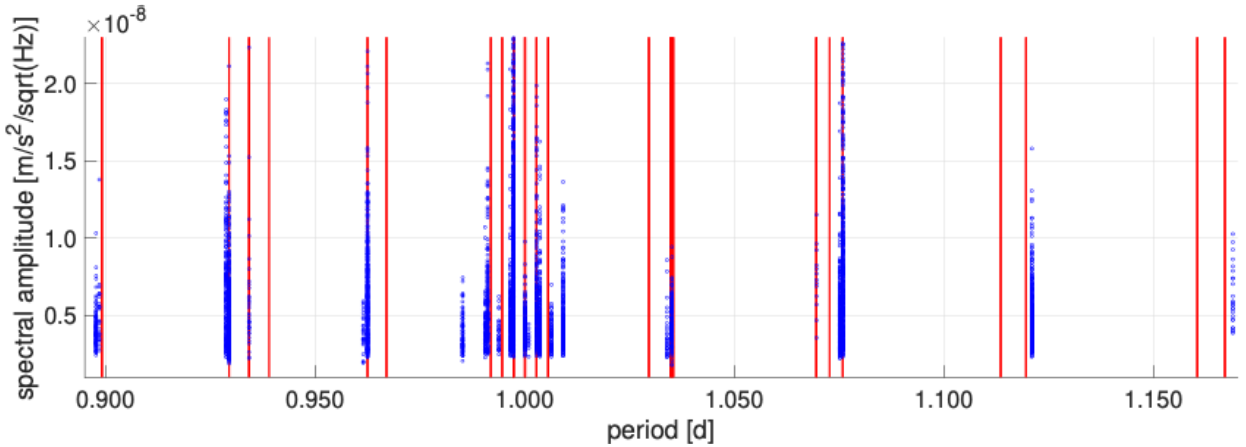


Fig. 12: Stacked 3-sigma plot of the residuals assigned to a grid cell [2]

stacked 3-sigma plot

zoom

- almost all extracted lines can be attributed to tidal periods
- several spectral replicas of terdiurnal tides

$$f_{\mathrm{A}} = |n f_s - f|$$

f signal frequency

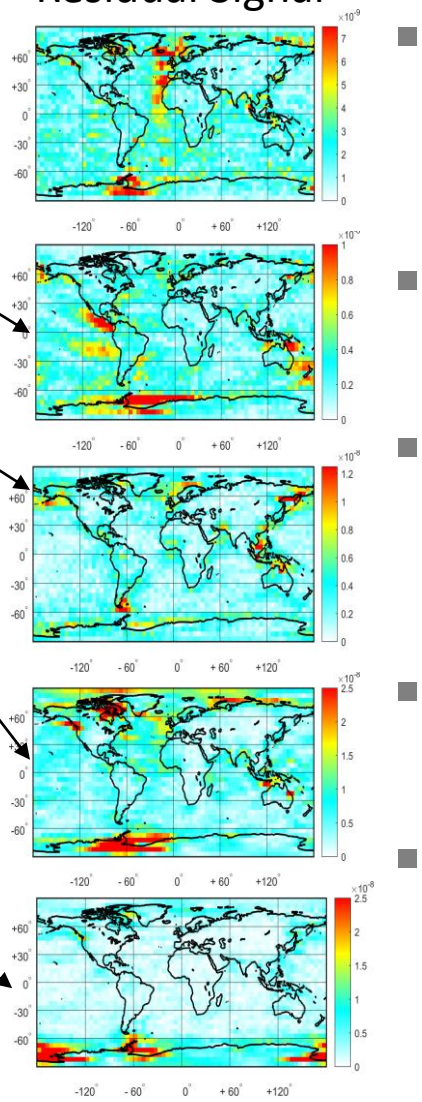
f_s sampling frequency

n integer multiple

Detected Tidal Lines

	Name(s)	Doodson Number	Period [d]	Amplitude [nm/s²/√Hz]	Aliasing Period [d]	TGP [% of M_2]
▽	O_1/MK_1	145.555	1.075795±4.215e-5	58.8/78.5	13.6	41.37
▽	M_2/KO_2	255.555	0.517526±1.764e-5	58.2/70.0	13.5	100.00
▽	$K_1/SP_1/MO_1$	165.555	0.997275±2.548e-5	42.0/59.8	2610.0	58.15
▽	P_1/SK_1	163.555	1.002751±2.320e-5	16.4/20.4	170.7	19.19
▽	J_1/MQ_1	175.455	0.962441±3.463e-5	15.5/24.7	27.9	3.25
a	$\beta_2/M(KS)_2$	256.554	0.516790±1.555e-5	14.3/19.7	14.0	0.30
a	OO_1	185.555	0.929429±2.831e-5	14.2/24.0	13.7	1.78
–	$^3L_2$	265.555	0.507905±1.636e-5	12.8/15.3	26.8	0.57
–	R_3/SK_3	383.555	1.003542±3.838e-5	12.4/17.0	150.5	-
▽	N_2/KQ_2	245.655	0.527432±1.551e-5	11.9/14.6	9.1	19.11
▽	$\mu_2/2MS_2$	237.555	0.536322±1.300e-5	11.8/16.9	7.1	3.05
a	τ_1/MP_1	147.555	1.069520±2.027e-8	10.7/18.7	14.7	0.54
a	$\alpha_2/M(SK)_2$	254.556	0.518262±1.708e-5	10.6/14.0	13.0	0.34
–	$^3M_3$	355.555	1.120892±3.465e-5	10.4/15.4	9.0	1.21
–	T_3/SP_3	381.555	1.009074±2.641e-5	10.2/14.5	82.6	-
a	SO_1	183.555	0.934169±2.125e-5	9.88/21.1	14.9	0.54
▽	S_2/KP_2	273.555	0.500000±7.968e-6	9.69/11.4	160.5	46.37
–	$^3N_2$	245.555	0.527515±1.631e-5	9.42/13.9	9.1	0.61
▽	$M_f/KO_o/MK_o$	075.555	13.660786±2.86e-3	9.02/11.0	-	14.84
▽	MS_4	473.555	0.519208±1.413e-5	8.51/11.5	12.5	0.00
–	$2MK_3/MO_3$	345.555	1.168828±2.349e-5	8.31/12.9	6.8	-
–	$2SM_2$	291.555	0.483624±1.253e-5	7.71/11.7	16.3	0.00
▽	λ_2	263.655	0.509243±5.860e-6	7.48/13.9	23.5	0.73
–	$^3M_1$	155.555	1.035051±2.809e-5	7.06/10.5	27.0	0.63
▽	$2N_2$	235.755	0.537724±5.463e-6	6.79/11.9	6.8	2.52
▽	$L_2/2MN_2/L_2A$	265.455	0.507985±9.632e-6	6.66/8.37	26.6	2.81
▽	MN_4	445.655	0.548843±1.523e-5	6.53/8.66	5.4	0.01
▽	S_1	164.556	1.000021±3.625e-8	6.21/8.87	318.8	0.45
▽	M_4	455.555	0.538130±8.882e-6	6.12/7.47	6.8	0.02
▽	ε_2/MNS_2	227.655	0.546971±5.739e-6	5.94/7.81	5.6	0.74
▽	M_6	655.555	0.448818±1.104e-5	5.54/6.66	4.5	0.00
–	S_3	382.555	1.006293±2.320e-5	5.32/6.85	106.7	0.00

Residual Signal



$m/s^2/\sqrt{Hz}$

- Obvious absorption of ocean tide model errors by the gravity field solutions
- Possible influence of data assimilation
- Too large residuals highly-likely related to the limits of the admittance approach
- Possible influence of seasonal modulations of tides
- …

▽ explicitly included in FES2014b

a admittance (interpolated)

– unmodeled:
not included in FES2014b and cannot be interpolated

Conclusion

- Analysis of Residuals show systematic effects
  - Shadow
  - Panel
  - Sensor characteristics
  - …
- Helps to improve the overall understanding of the Satellite platform
- Helps to improve the understanding of the environment of the Satellites
  - E.g. Thermal Couplings
- Helps to improve background modelling, such as Ocean tide signals
  - Ocean tide errors at over 30 tidal frequencies were identified
  - Major tides, gravitationally excited tides of degree-3, non-linear tides, radiational tides

References

- [1] Duwe, Mathias, Igor Koch, and Jakob Flury. "Residual Patterns in GRACE Follow-On Laser Ranging Interferometry Post-Fit Range Rate Residuals." *Advances in Space Research* 73.12 (2024): 5769-5782.

- [2] Koch, Igor, Mathias Duwe, and Jakob Flury. "Residual and unmodeled ocean tide signal from 20+ years of GRACE and GRACE-FO global gravity field models." *Journal of Geophysical Research: Solid Earth* 129.9 (2024): e2024JB029345.