Precise orbit determination for low Earth orbit satellite during maneuver periods

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Outline

- Motivation
- Bernese POD strategy
- Internal consistency check
- External orbit validations
- Conclusions

Motivation

- Low Earth Orbit (LEO) satellite perform maneuvers to,
  - overcome highly-perturbed in-flight conditions
  - maintain pre-defined trajectory
  - keep formation/constellation flying
  - avoid threatening collisions…
- However the challenges are,
  - maneuvers can be significantly different for various satellite missions
  - (reduced-) dynamic Precise Orbit Determination (POD) gets worse
  - follow-on scientific research might be influenced by imperfect orbit…

Motivation

- Research case 1 : Sentinel-3 (A/B)
  - Part of the fleet of European Space Agency's Copernicus Earth observation satellites
  - High-precision GPS receiver and Satellite Laser Ranging (SLR) for POD and validation
  - Data sets: all maneuver days in 2020, a reference day (w/o maneuvers) is selected

Sentinel-3A maneuver information*

DOY	Duration [s]	Acceleration [mm/s^2]
20071	889.7	2.487
20169	3.4	1.885
20245	N/A	NA
20246	774.8	2.429
20337	13.9	0.615
20351	997.6	2.403

Sentinel-3B maneuver information*

DOY	Duration [s]	Acceleration [mm/s^2]
20036	718.6	2.658
20099	673.8	2.632
20148	2.9	1.913
20211	1.9	1.901
20281	885.6	2.587
20351	13.8	0.609

* In telemetry data, the start and end accelerations are different, the average of them is shown.

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Motivation

- Research case 2 : GRACE-FO (C/D)
  - A NASA/DLR Earth gravitational science satellite formation
  - High-precision GPS receiver, SLR and K-Band Radar (KBR) for POD and validation
  - Data sets: all orbit maneuver days since launch

GRACE-FO-C maneuver information*

DOY	Duration [s]	Acceleration [mm/s²]
18144	127	0.157
18145	416	0.144
18146	423	0.144
18173	49	0.143
18295	735	0.144
21307	1790 and 31	0.145

GRACE-FO-D maneuver information*

DOY	Duration [s]	Acceleration [mm/s²]
18144	126	0.159
18146	406 and 413	0.148
18173	84	0.148
19078	17	0.149
20253	5	0.130
21307	1790	0.149

* Durations and accelerations are from the spacecraft-event (TN-01a_SCE.txt) file.

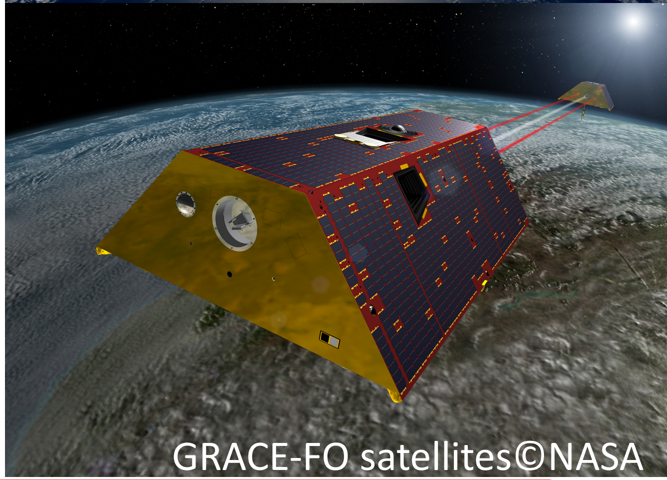
Bernese POD strategy

- Software: Bernese GNSS Software v5.5
- POD solutions: reduced-dynamic and kinematic
- Satellite geometry: macro-model
- Gravitational and non-gravitational forces
- Dynamic parameters:
  - orbit elements
  - constant empirical acc.
  - **constant maneuver acc. in satellite body-fixed frame**

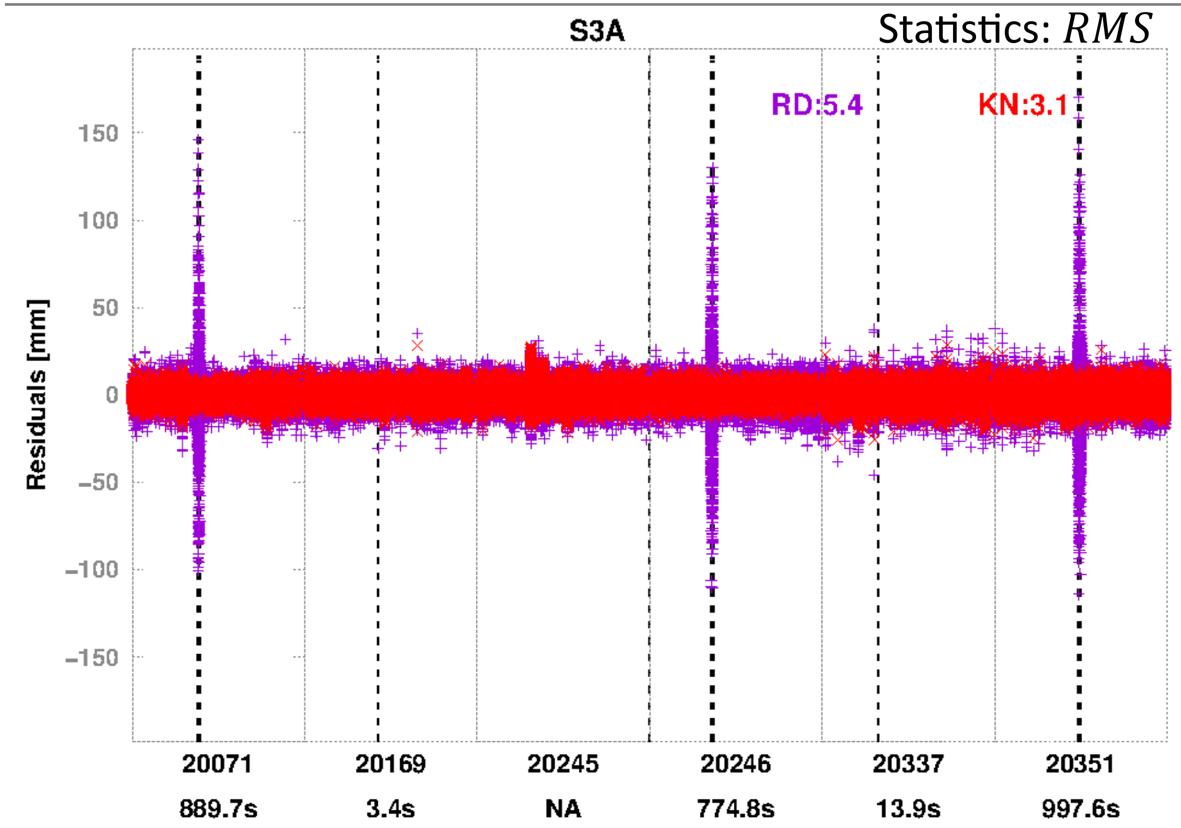
No a-priori maneuver accelerations, only durations are used!

- Pseudo-stochastic parameters:
  - piece-wise constant acc.
  - **velocity pulses depending on maneuver time span**
- **Single receiver integer ambiguity resolution (IAR)**
  - No IAR during maneuver periods!

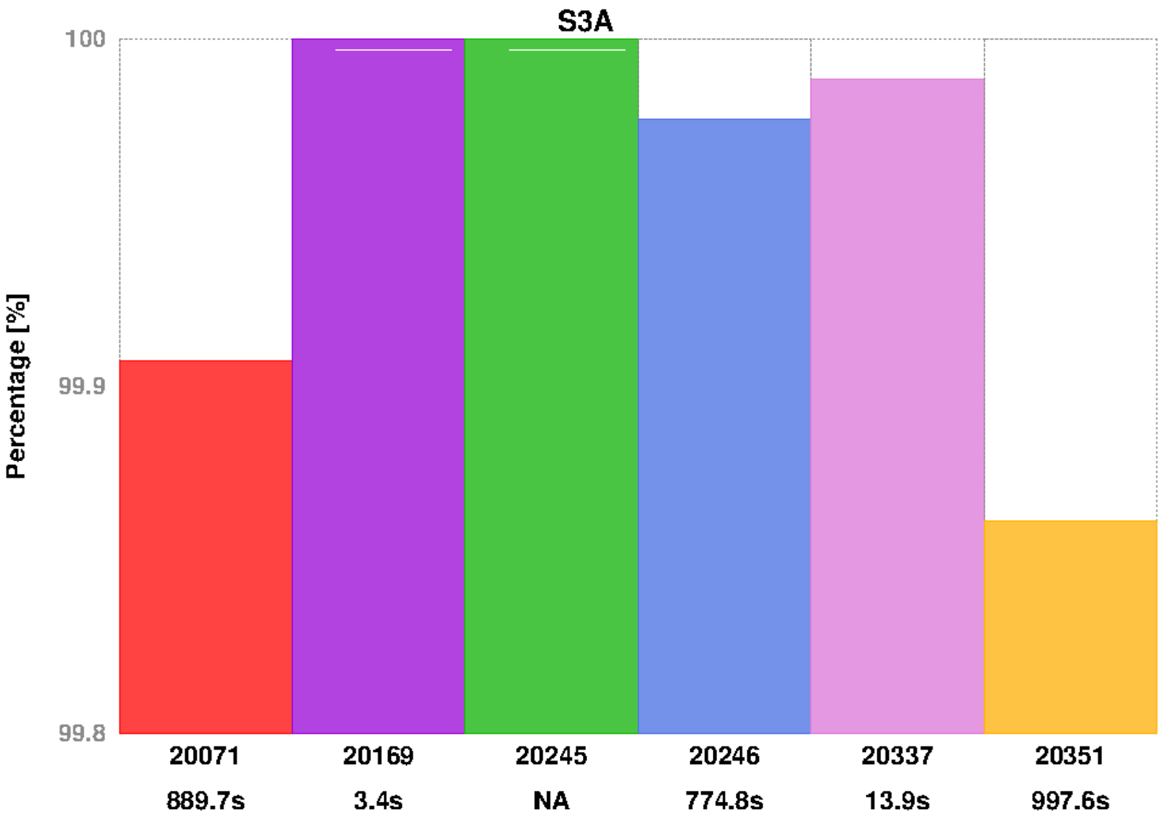

Sentinel-3 satellite ©ESA


GRACE-FO satellites©NASA

Internal orbit consistency: residuals



Ionosphere-free carrier-phase residuals and RMS statistics for the POD solution of Sentinel-3A maneuver and reference days.
RD: Reduced-dynamic; KN: Kinematic



Kinematic orbit availability in 24-hrs for Sentinel-3A.
The days (YYDOY) and maneuver durations ([s]) will be indicated at the x-axis in all figures

- Reduced-dynamic POD for small-maneuver days works fine, only visible impact from strong maneuvers.
- Kinematic POD has high availability and is hardly influenced by maneuvers, can be used as reference orbit.

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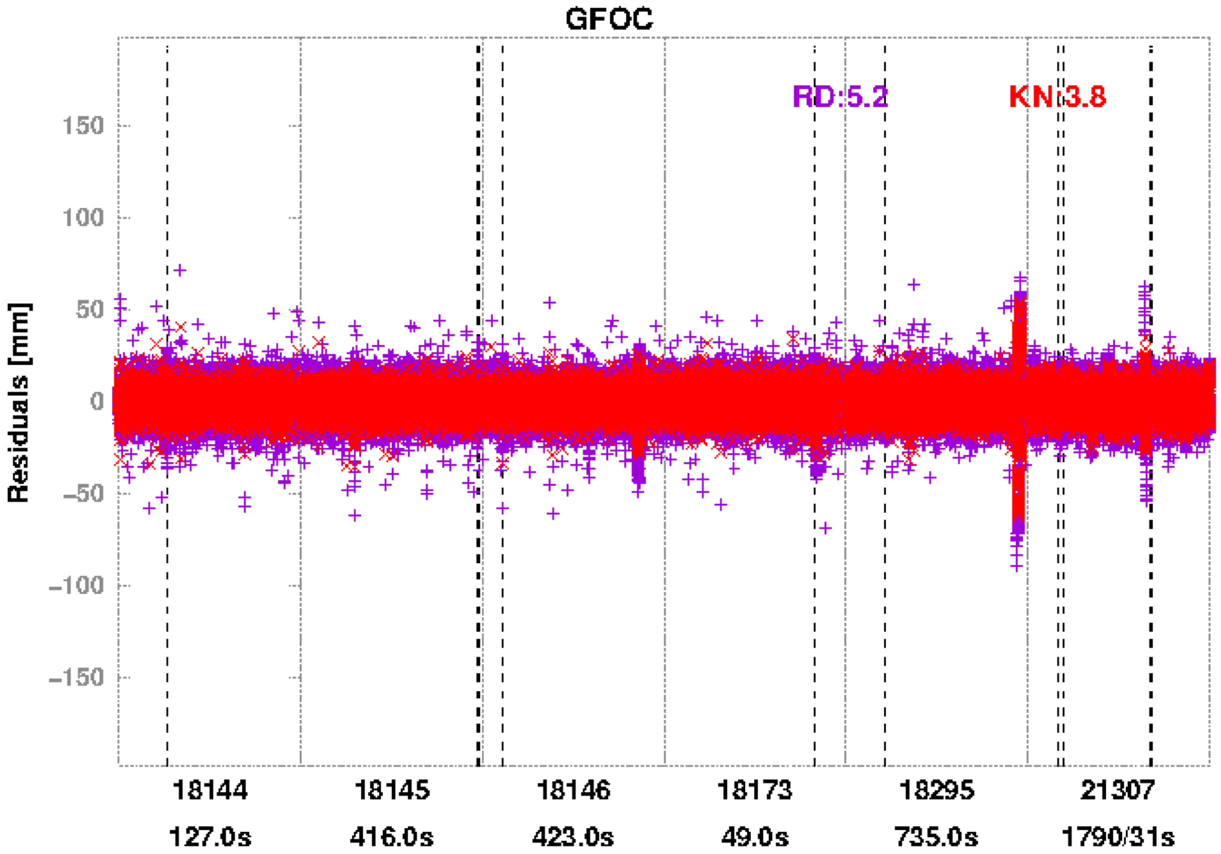
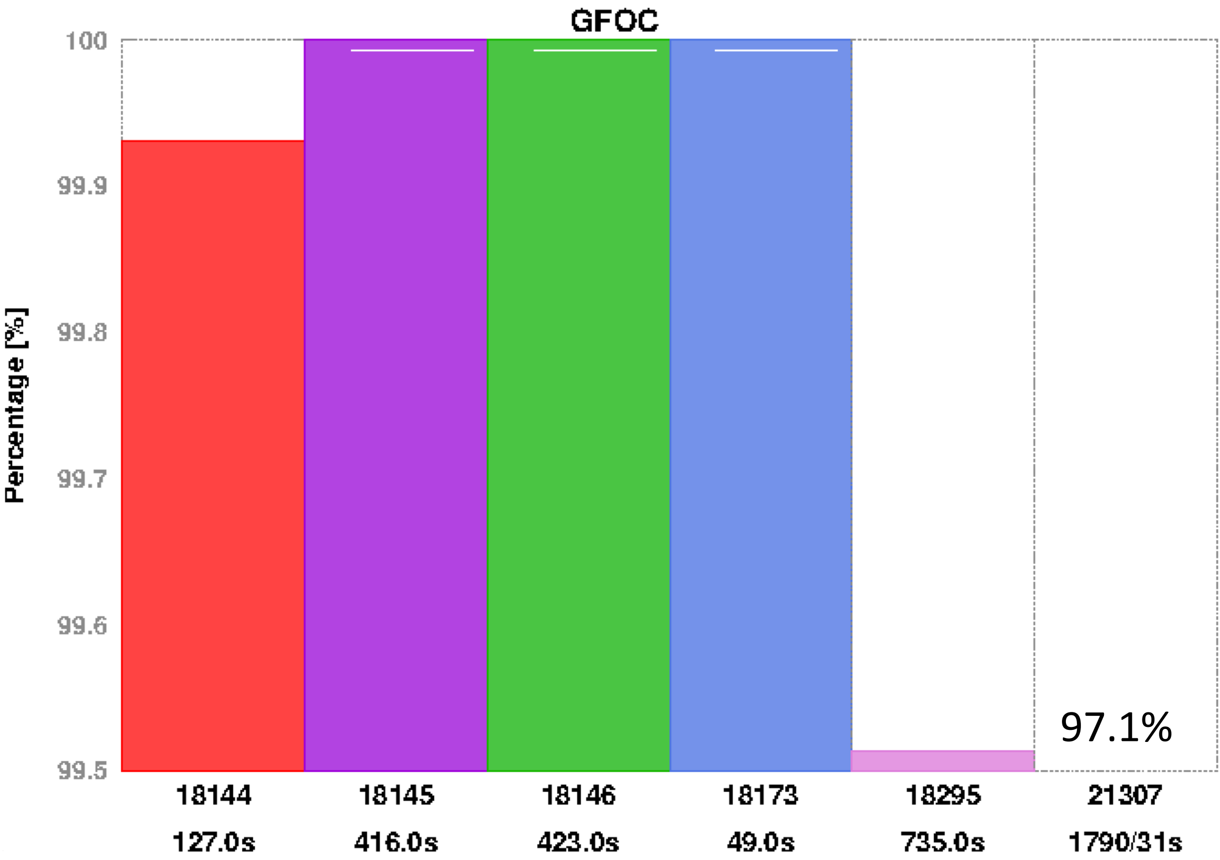
Internal orbit consistency: residuals



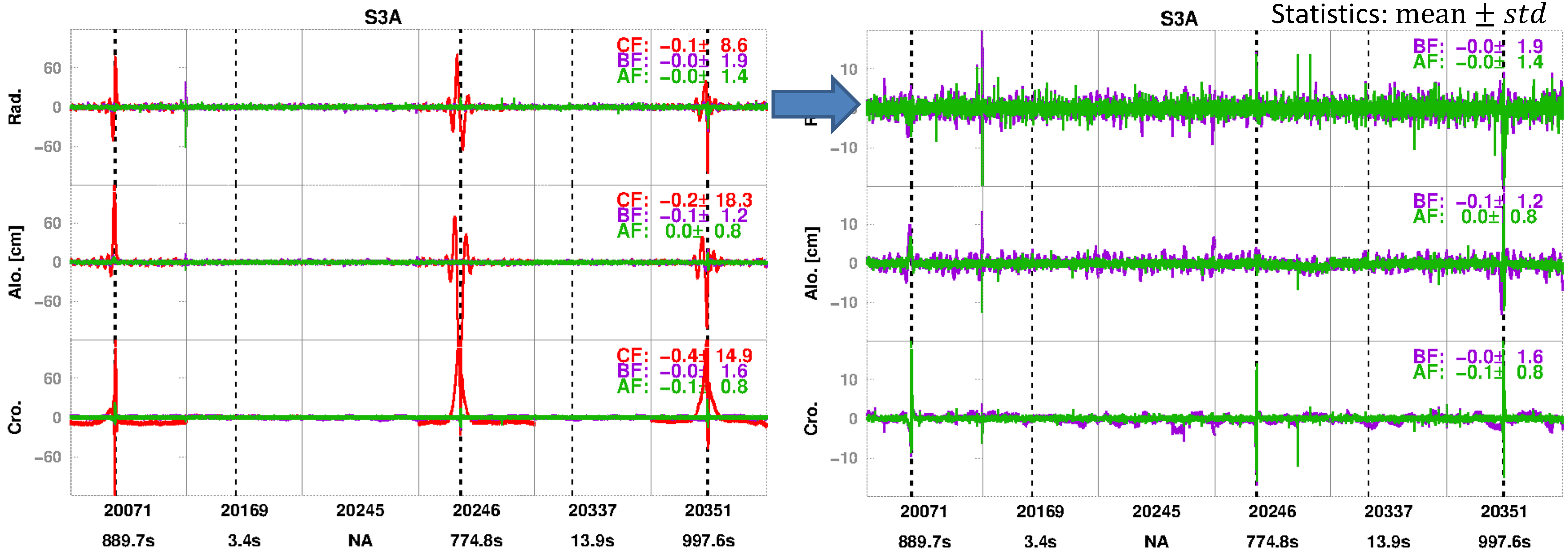
Ionosphere-free carrier-phase residuals and RMS statistics for the POD solution of GRACE-FO-C maneuver and reference days



Kinematic orbit availability in 24-hrs for GRACE-FO-C

- GRACE-FO satellites maneuvers can be better modeled due to smaller magnitude.

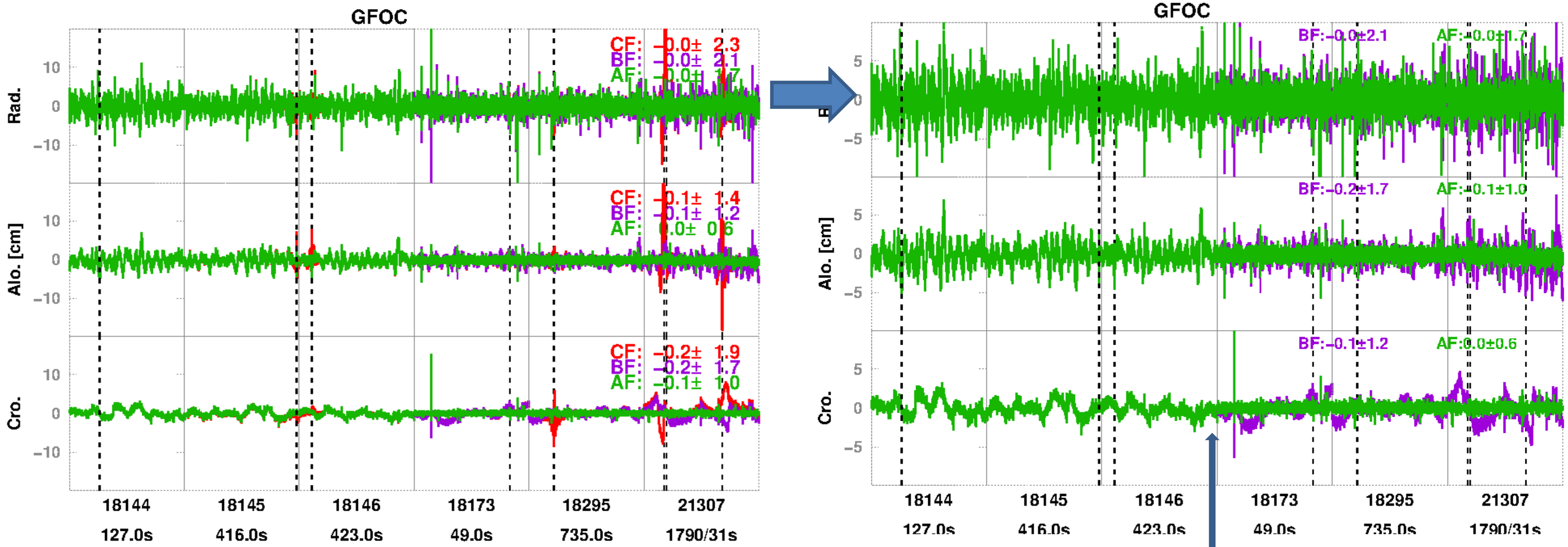
Internal orbit consistency: RD-KN orbit



Kinematic/reduced-dynamic orbit consistency for the different Sentinel-3A orbit solutions. CF: only estimate accelerations; BF: CF + velocity pulses ($\sigma = 1m/s$) depending on the maneuver duration; AF: BF + IAR, final POD result for the next analyses

- Additional velocity pulses estimation is crucial for days with strong maneuvers.
- IAR further constrains parameter estimation and enhances POD for maneuver days.

Internal orbit consistency: RD-KN orbit



Kinematic/reduced-dynamic orbit consistency for the different GRACE-FO-C orbit solutions

The operational CODE OSB product (for IAR) becomes available since mid-2018
The repro products would be available longer back.

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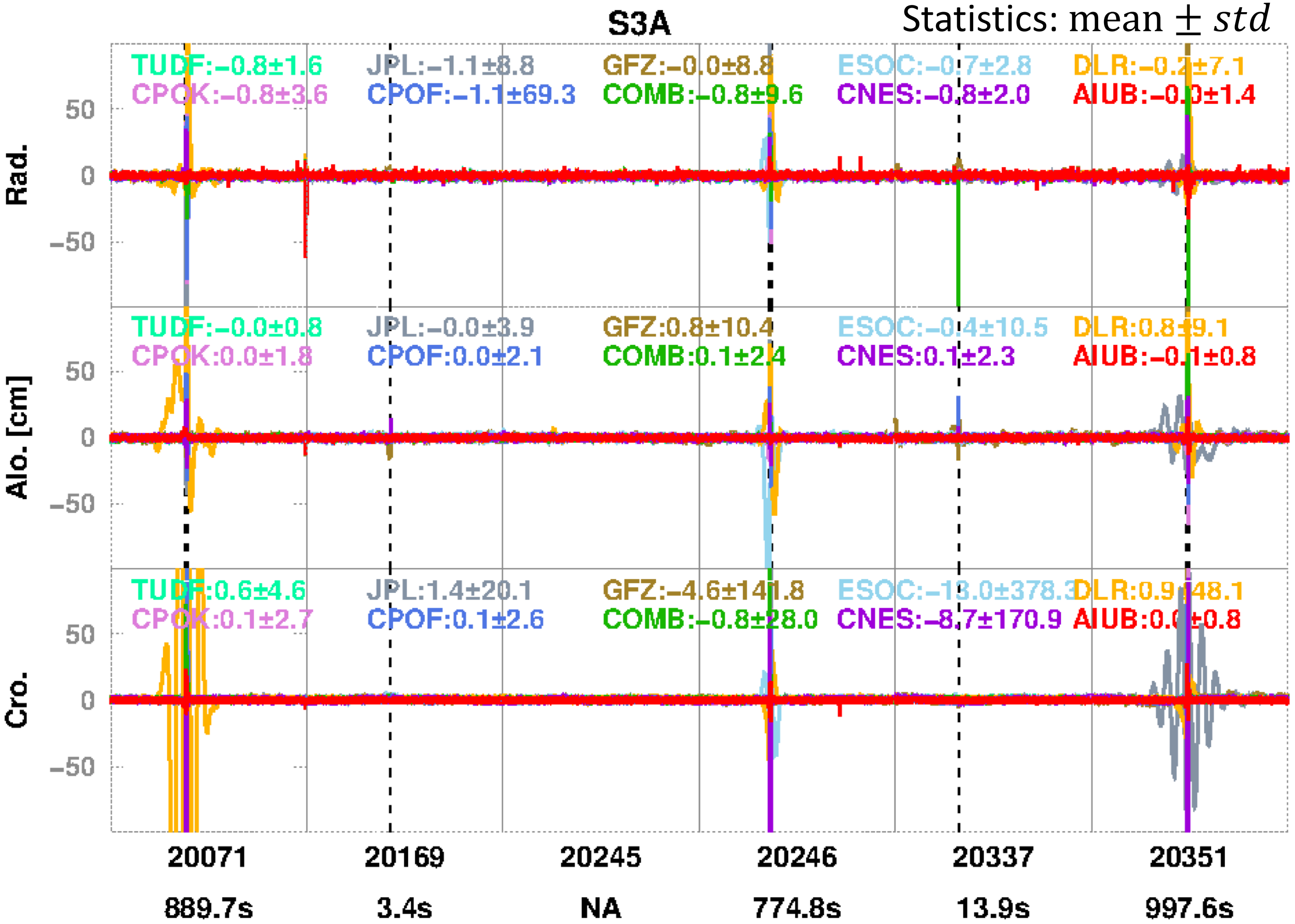
External orbit validation: comparisons

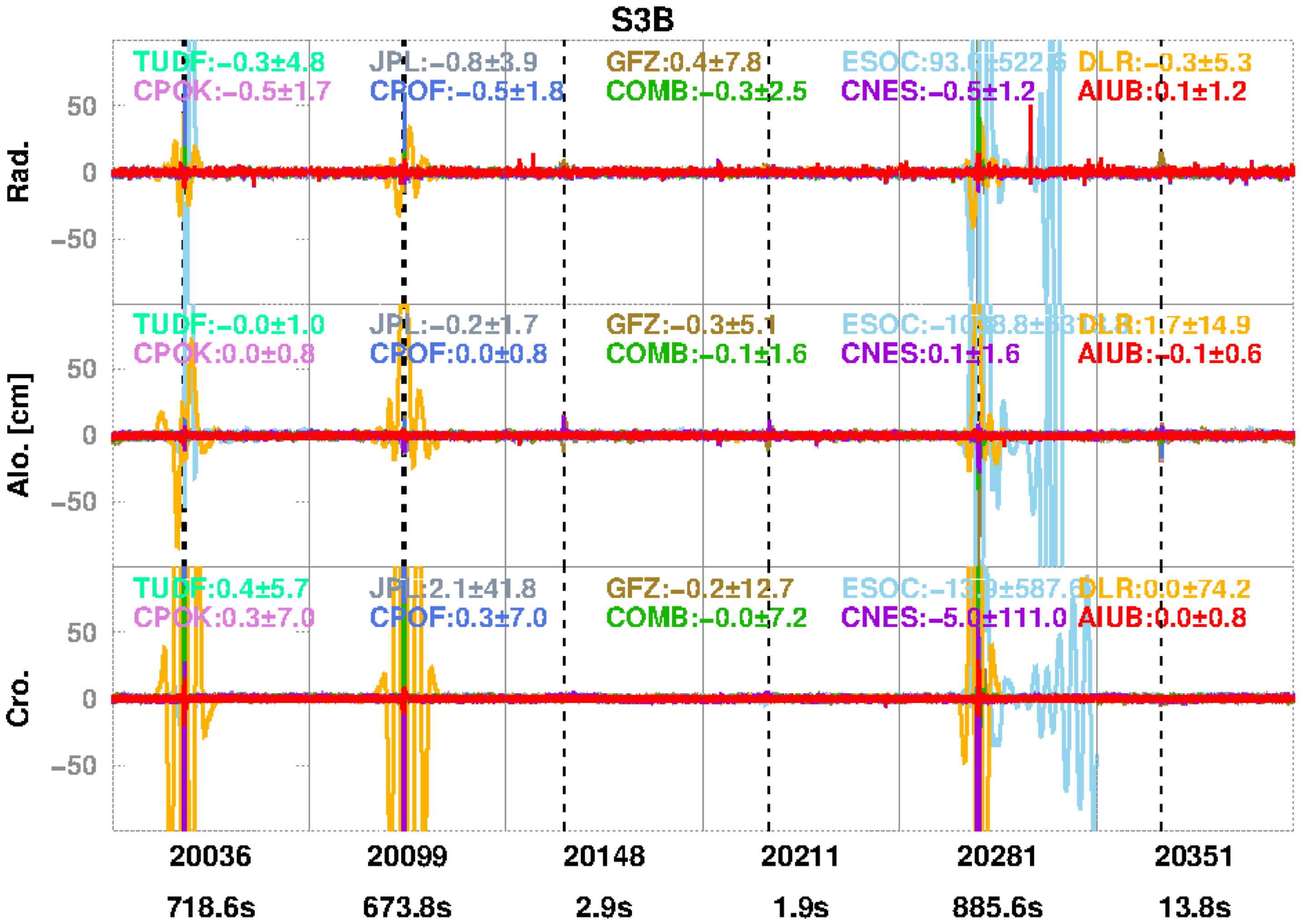


Consistency between the AIUB ambiguity-fixed kinematic orbit and orbits delivered by different members of the POD Quality Working Group for Sentinel-3A. No outlier screening

List of institutes with POD service for maneuver days (alphabet in descending order):

TUDF: Delft University of Technology
JPL: Jet Propulsion Laboratory
GFZ: German Research Centre for Geosciences
ESOC: European Space Operations Centre
DLR: German Aerospace Centre
CPOK: Official CPOD Orbit, kinematic
CPOF: Official CPOD orbit, reduced-dynamic
COMB: Combined solution of different orbits
CNES: French Space Agency
AIUB: Astronomical Institute, University of Bern

External orbit validation: comparisons



Consistency between the AIUB ambiguity-fixed kinematic orbit and orbits delivered by different members of the POD Quality Working Group for the Sentinel-3B. No outlier screening

Please notice that the operational orbits from different institutes do not necessarily make use of their best-tuned maneuver handling strategy

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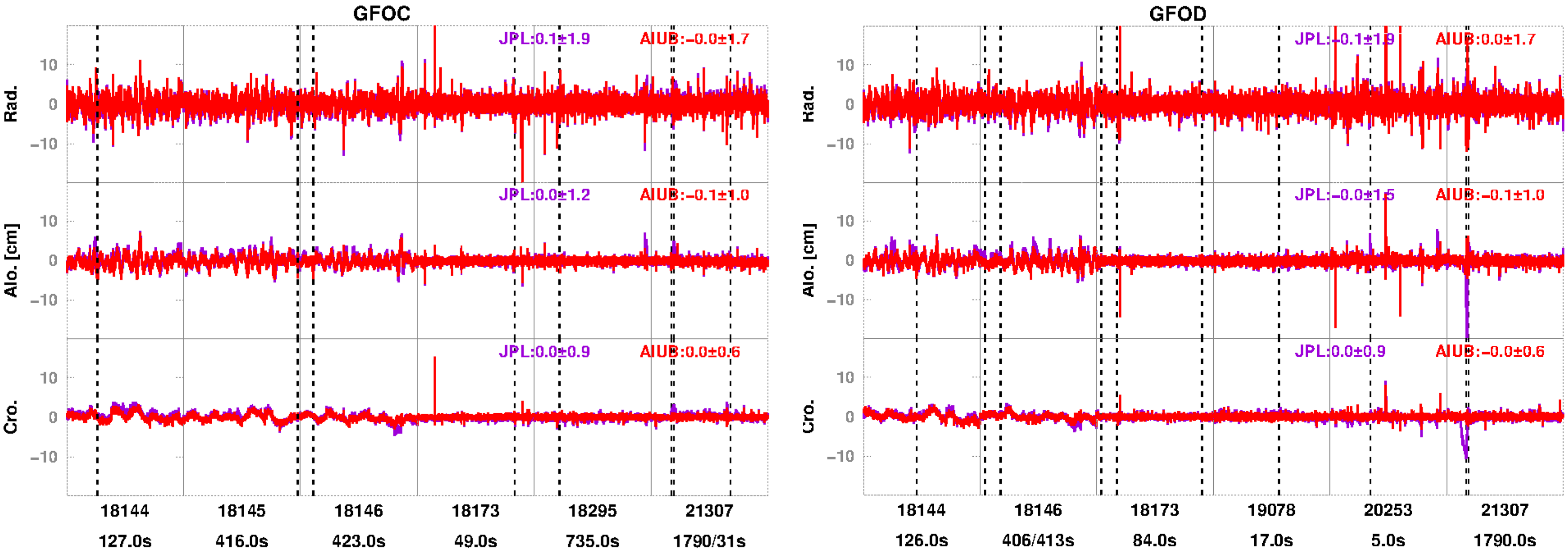
External orbit validation: comparisons



Consistency between the AIUB ambiguity-fixed kinematic orbit, and AIUB reduced-dynamic orbits and JPL official orbits for GRACE-FO-C (left) and GRACE-FO-D (right). No outlier screening

- PODs for the maneuvering GRACE-FO satellites are more stable due to smaller maneuver accelerations.

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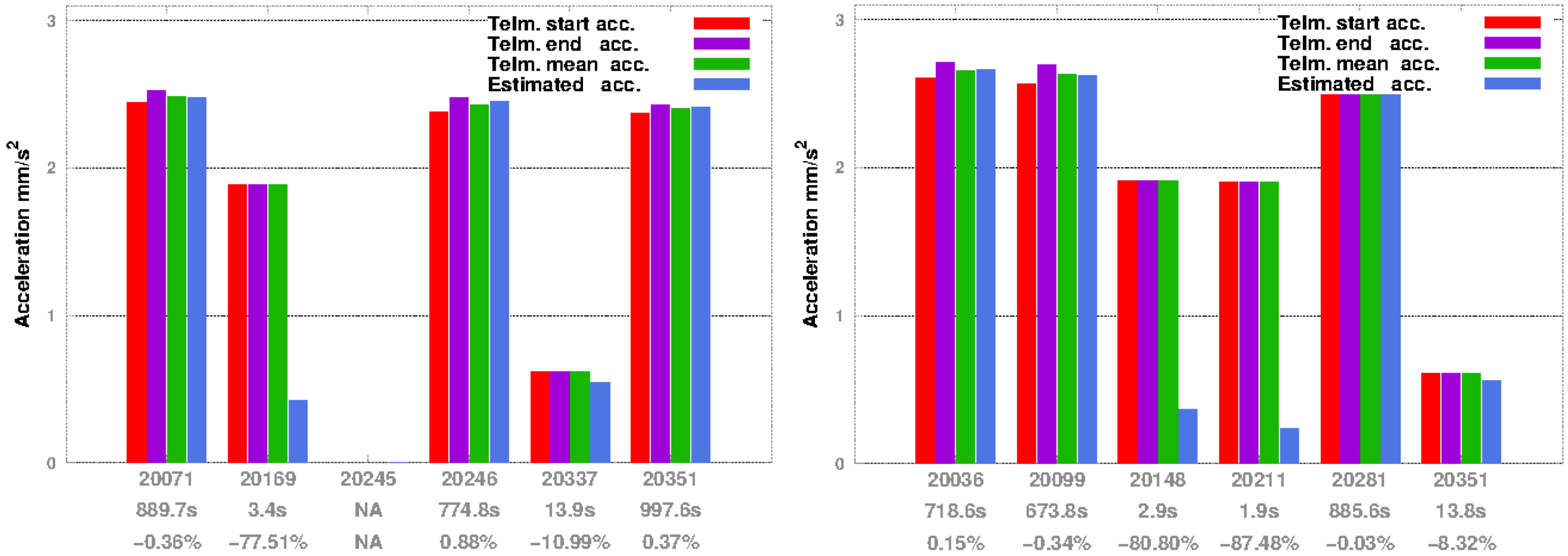
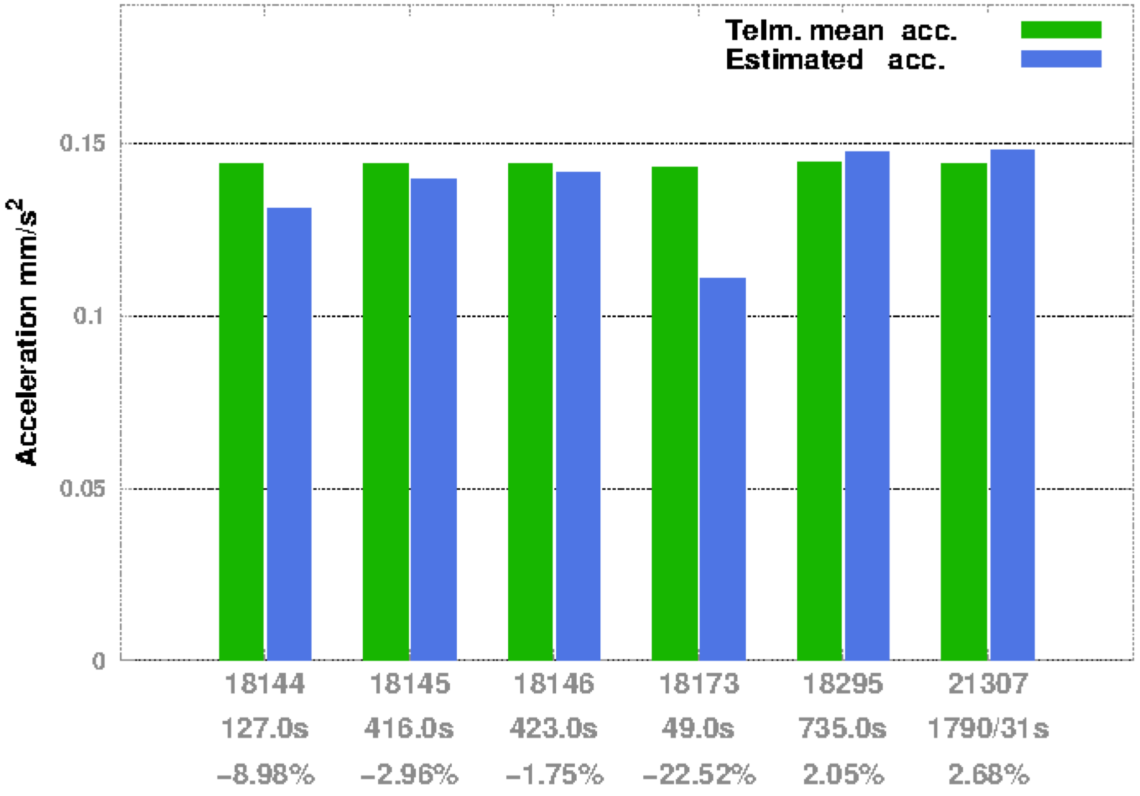
External orbit validation: telemetry

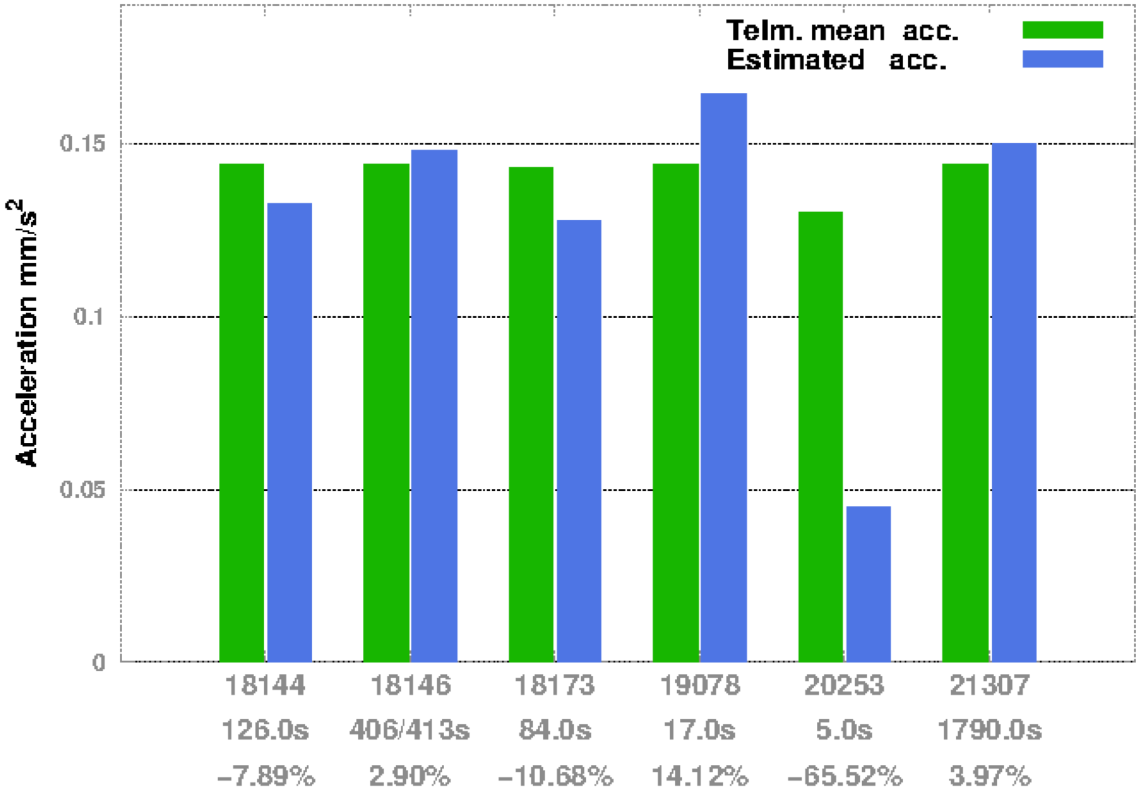


Comparison between the start/end/mean maneuver accelerations from the telemetry data and the AIUB-estimated accelerations for Sentinel-3A (left) and Sentinel-3B (right). The differences are described as percentage ([%]) in the bottom

- For days with strong and long maneuver, the estimated accelerations agree well with the telemetry data.
- For days with small and short maneuver, the estimated accelerations clearly differ from the telemetry data.

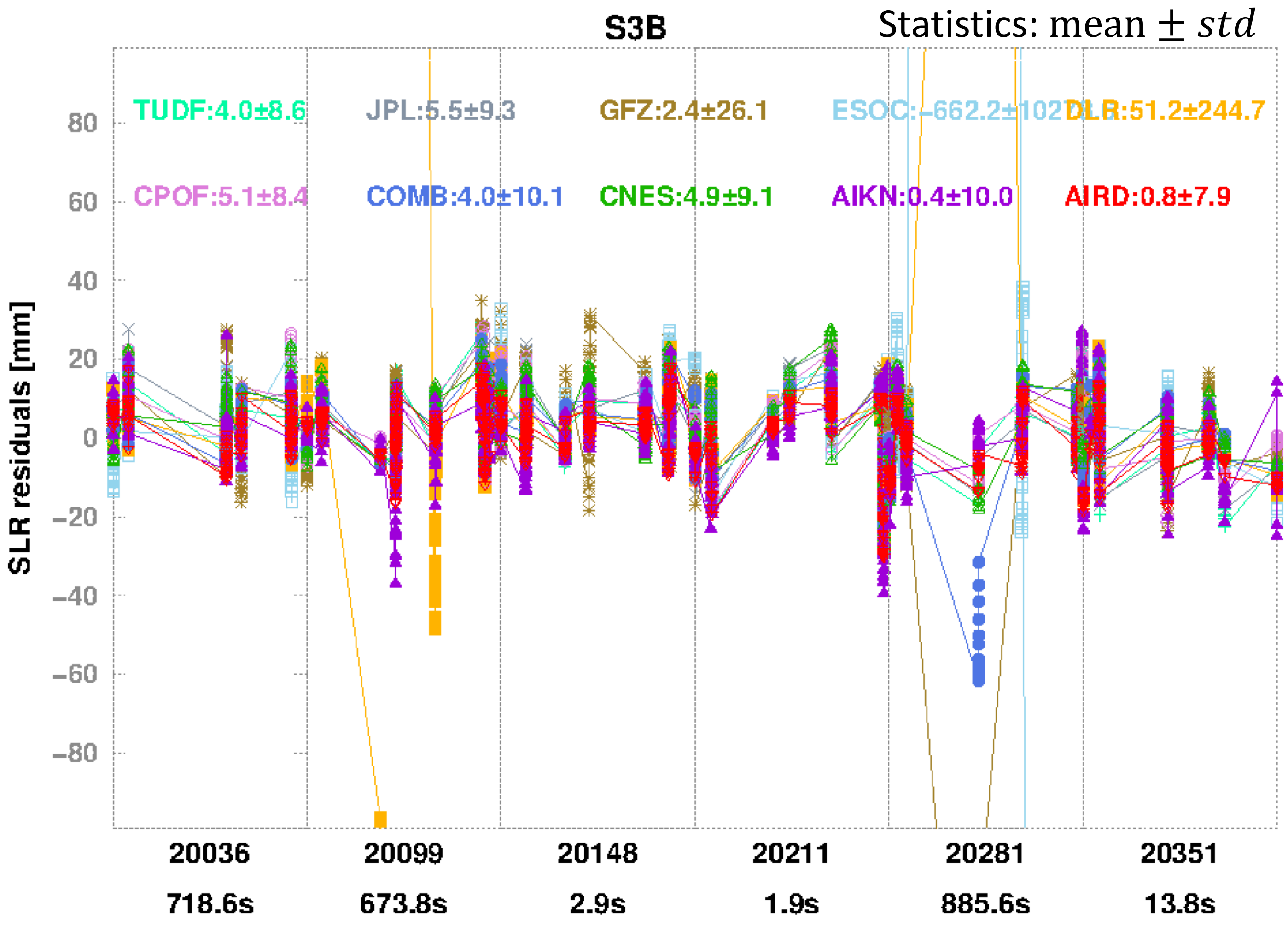
External orbit validation: telemetry





Comparison between the mean maneuver accelerations from the telemetry data and the AIUB-estimated accelerations for GRACE-FO-C (left) and GRACE-FO-D (right). The differences are described as percentage ([%]) in the bottom

External orbit validation: SLR



SLR validations to the different CPOD institute orbits for Sentinel-3B.
10 selected stations, no data screening

Luckily, SLR validations are available for all the Sentinel-3B maneuvering days.

SLR validations show that some orbits can be significantly influenced due to maneuver processing that influences periods outside of maneuvers.

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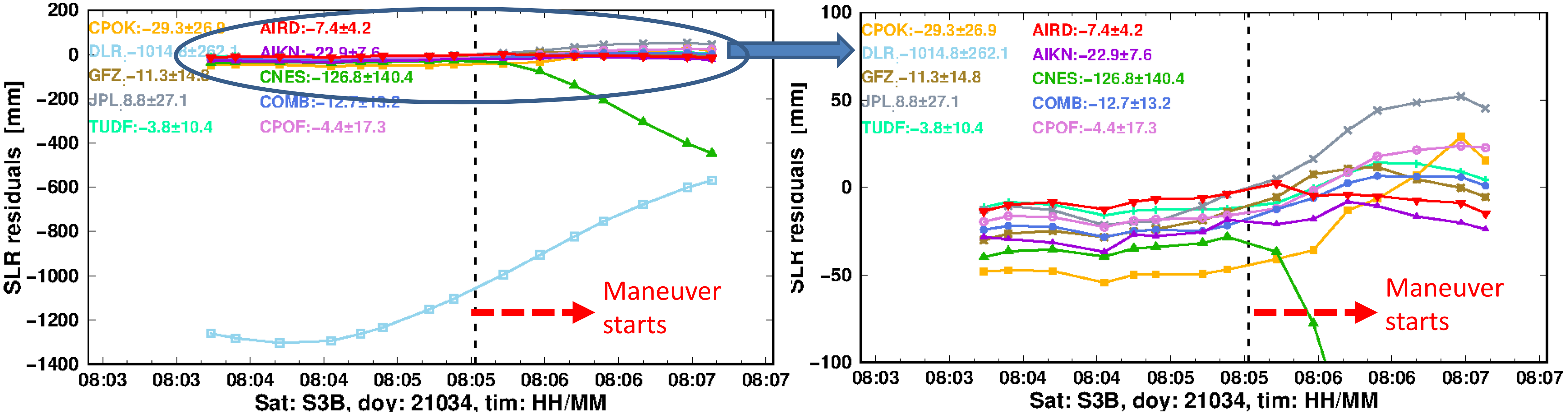
External orbit validation: SLR



A single SLR tracking pass crossing the maneuver period is available for Sentinel-3B from the Tahiti SLR station on day 21034, with a strong maneuver lasting for 774.3s

- AIUB orbit is among the best in terms of agreement with SLR measurements crossing maneuvers.

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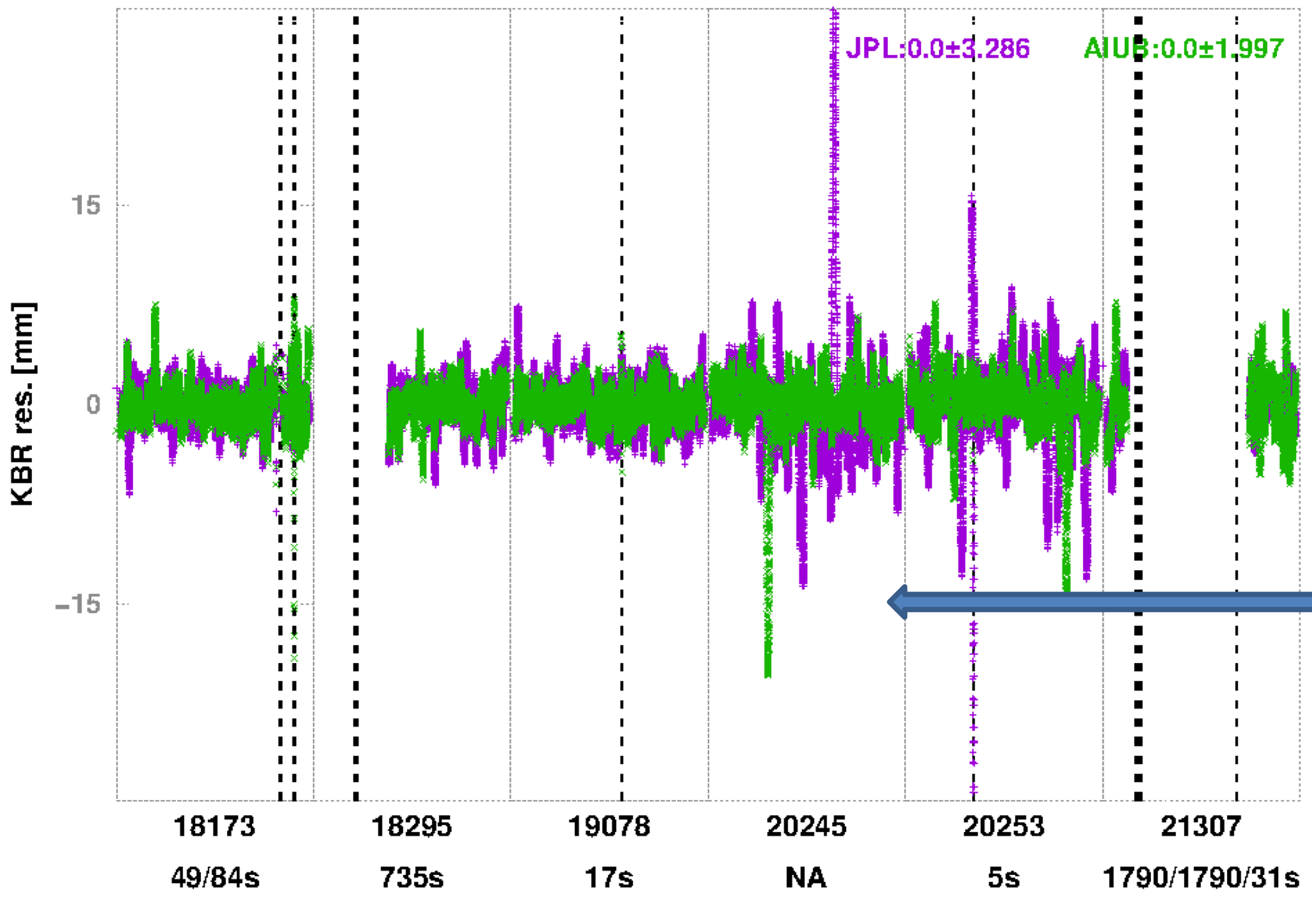
External orbit validation: KBR



Again, take day 20245 as reference.

Please note the receivers suffered from the switched on of flex power mode IV since 14-Feb-2020. Issues solved after 22-Jul-2021.

K-Band radar validations to the AIUB GRACE-FO orbit solutions and the JPL official orbit

- AIUB orbit solutions show reliable POD quality for the maneuver days.

Conclusions

- Kinematic orbit is free from satellite dynamics, can be used as a good reference orbit.
- Additional velocity pulses estimation is crucial for days with strong and long maneuvers, in particular for the Sentinel-3 satellites.
- Integer ambiguity resolution further constrains parameter estimation and enhances POD for maneuver days.
- The estimated accelerations agree well with telemetry data for days with long and strong maneuvers, but show large discrepancy for days with short and small maneuvers.
- SLR and KBR validations can be used to check the POD performances during maneuvers.

References

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