Performance of dynamic and ambiguity-fixed GNSS-derived LEO orbits in SLR validation and network calibration

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Motivation

- Numerous geodetic satellites are in low Earth orbit (LEO)
- Precise orbit determination (POD) by GNSS (GPS), some tracked by Satellite Laser Ranging (SLR)
- GNSS-based LEO POD has witnessed remarkable quality improvements in recent past (e.g., more accurate modeling of gravitational and non-gravitational forces, single-receiver ambiguity fixing, ...)
  $\rightarrow$ cm accuracy and precision possible

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SLR to LEO satellites

- allows for independent validation of GNSS-derived orbits
- allows to measure orbit errors not only in radial, but also in lateral directions
- can be used to calibrate SLR stations (coordinates, range and timing biases) *if* we have confidence in GNSS-derived orbits

GPS-based POD of LEO satellites

- Bernese GNSS Software v5.3
- State-of-the-art models
  - Macro models for non-gravitational forces
  - In-flight calibrated GPS antenna phase patterns
  - Spacecraft parameters (attitude, CoM, sensor locations, etc.)
- Carrier phase ambiguity fixing:
  - Single-receiver ambiguity resolution using GPS products of Center for Orbit Determination in Europe (CODE), including new signal-specific satellite phase biases
  - Ties LEO orbit to IGSxx reference frame
  - Horizontal components benefit most, only weak constraint in vertical direction

CODE clock and phase bias product

Ambiguity-fixed GNSS clock corrections and phase bias products (enabling undifferenced ambiguity-resolution) of CODE available:

- Operationally generated
- IGS Final product line:
  - `ftp://ftp.aiub.unibe.ch/CODE`
  - `ftp://cddis.gsfc.nasa.gov/pub/gnss/products`
  - Starting from 1 January 2019
- MGEX product line:
  - `ftp://ftp.aiub.unibe.ch/CODE_MGEX/CODE`
  - `ftp://cddis.gsfc.nasa.gov/pub/gnss/products/mgex`
  - Starting from 1 July 2018
- See also `ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT`

Models used for POD

- Earth gravity field: GOCO05S (120×120)
- Solid Earth tides: IERS2010
- Pole tides: IERS2010
- Ocean pole tides: EOT11a (50×50)
- Atmospheric densities/horizontal wind model: DTM2013 / HWM14
- Earth reflectivity/emissivity: CERES 2007
- Transmitting antenna PCO/PCV: igs14.atx
- Receiver antenna PCV: in-flight calibration (iterative residual stacking)

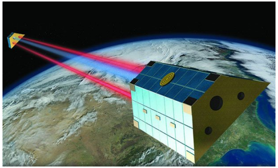
Satellites considered

Swarm-A/B/C:

- Magnetic field
- Launched: 22 Nov 2013
- Altitude: 460 km (A/C), 510 km (B)

Sentinel-3A/B:

- Altimetry
- Launched: 16 Feb 2016 (A), 25 Apr 2018 (B)
- Altitude: 810 km

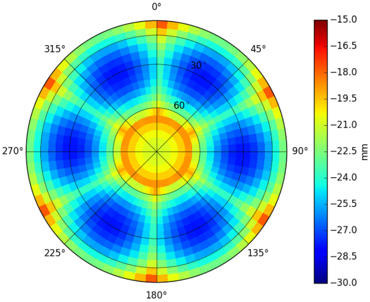


GRACE Follow-On C/D:

- Gravity field
- Launched: 22 May 2018
- Altitude: 500 km

Analysis of LEO SLR data

- Compute SLR residuals based on
  - known LEO satellite orbit, attitude, geometry, LRA characteristics



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  - outlier threshold of 20 cm, elevation cutoff of 10°.

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- Compute partials of range measurements w.r.t.
  - satellite position (in RTN or s/c body frame)
  - station position (in NEU frame)
  - SLR range and timing bias

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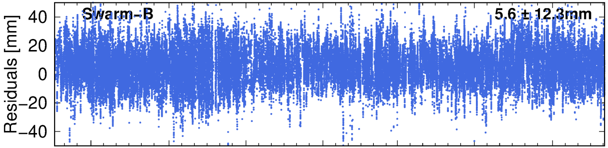
  - SLR range and timing bias
- From partials and residuals, form/solve normal equations
  - Correlations (station height and radial orbit component; time offset and along-track component)
  - A priori constraints or well observable set of parameters

SLR residuals Swarm-B, (reduced-) dynamic



Amb.-float, no non-grav. modeling

SLR observations of 14 high-performance SLR stations, SLRF2014 station coordinates used, no parameters estimated.
Time span: 18/154 - 19/224
(3 Jun 2018 - 12 Aug 2019)

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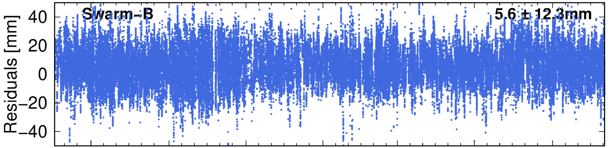

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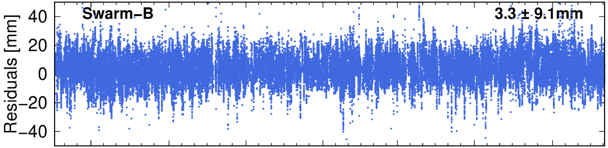

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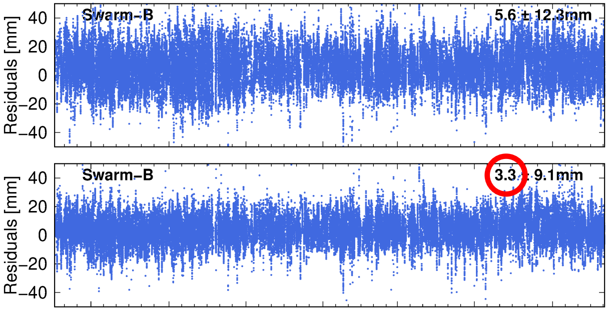

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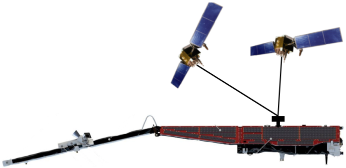

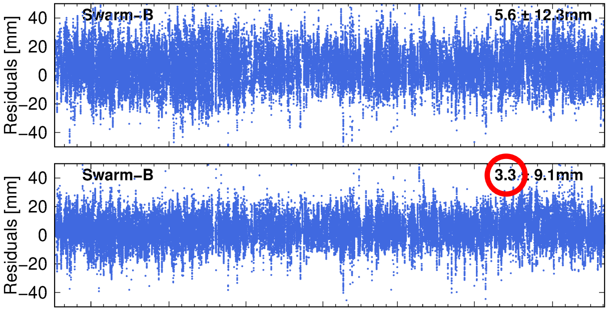

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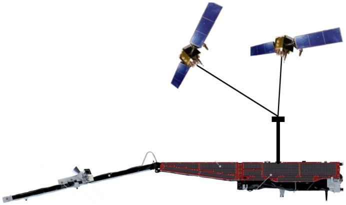

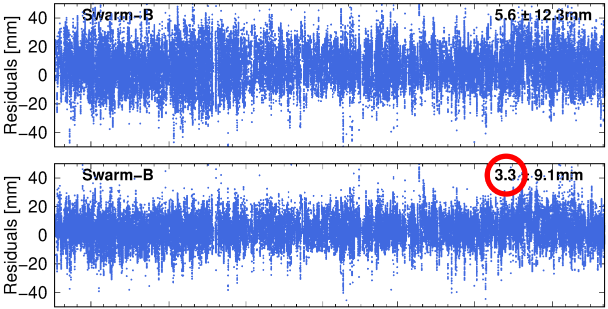

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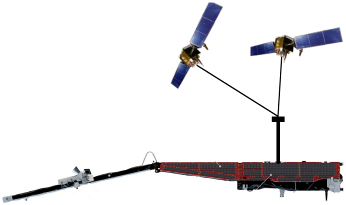

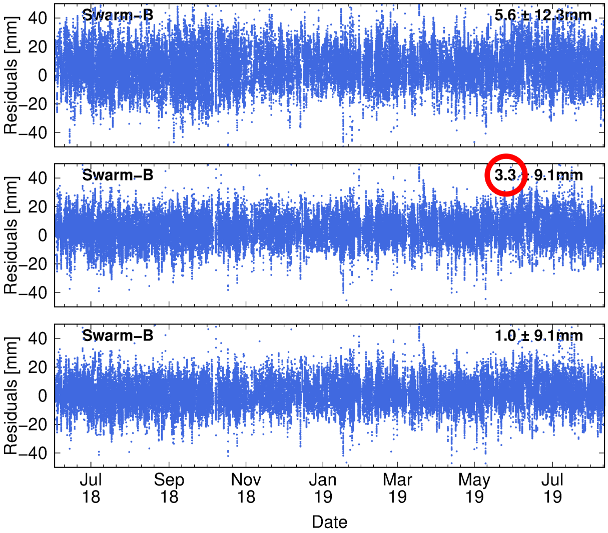

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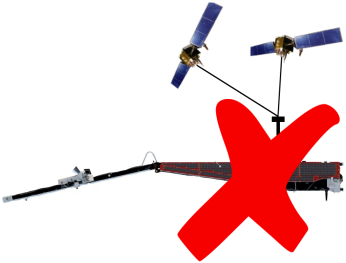

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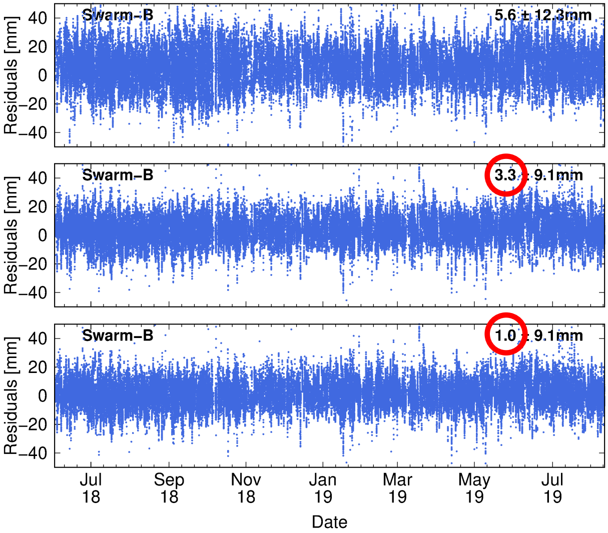

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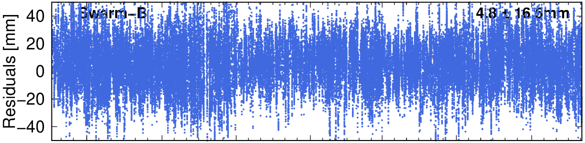
SLR residuals Swarm-B, kinematic

Kinematic orbits: Purely geometrically derived from GPS observations, fully independent on the force models used for dynamic LEO POD.



Amb.-float (16.5 mm)

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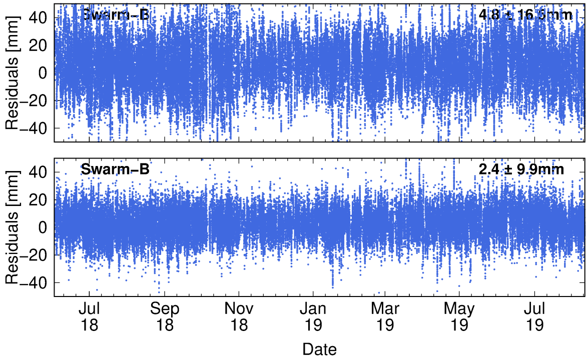

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Amb.-fixed (9.9 mm)

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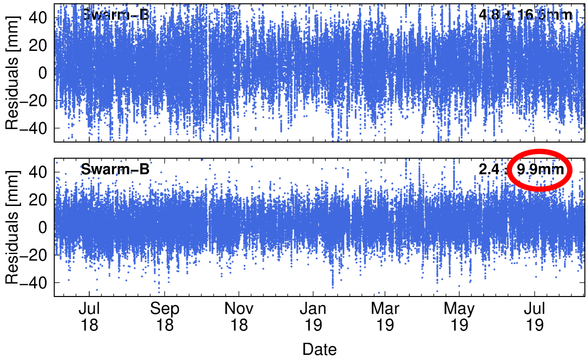
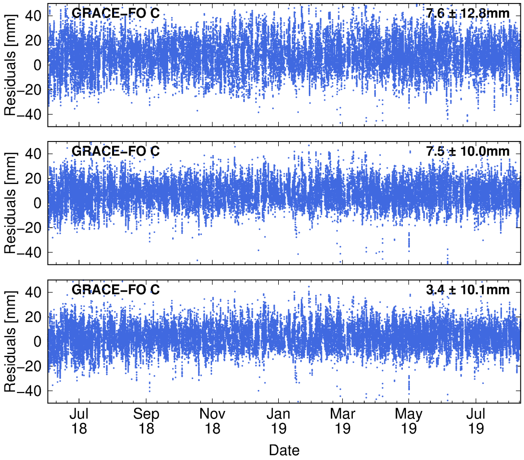


Amb.-float (16.5 mm)

Amb.-fixed (9.9 mm)

SLR STD comparable to ambiguity-fixed dynamic orbits (9.1 mm)!
$\longrightarrow$ limitations of SLR?

SLR residuals GRACE-FO, (reduced-) dynamic



Amb.-float,
no non-grav.
modeling

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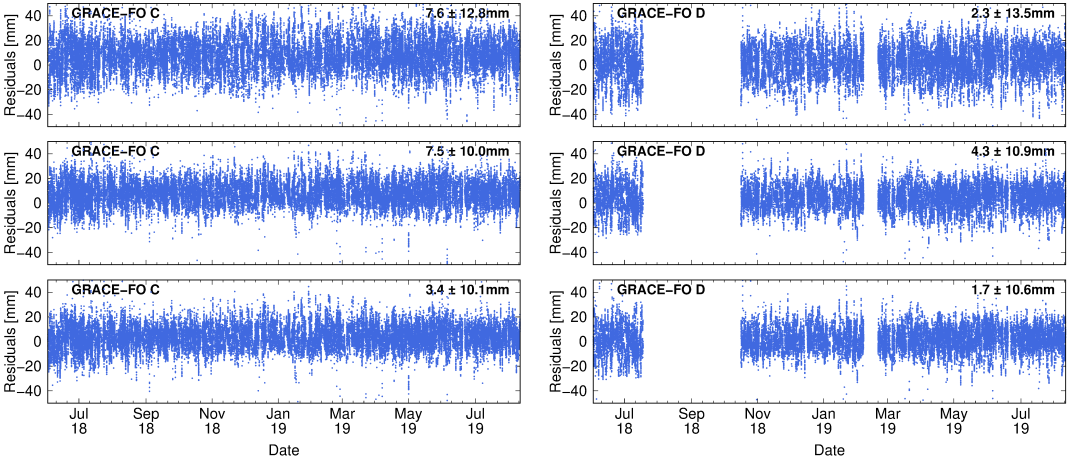

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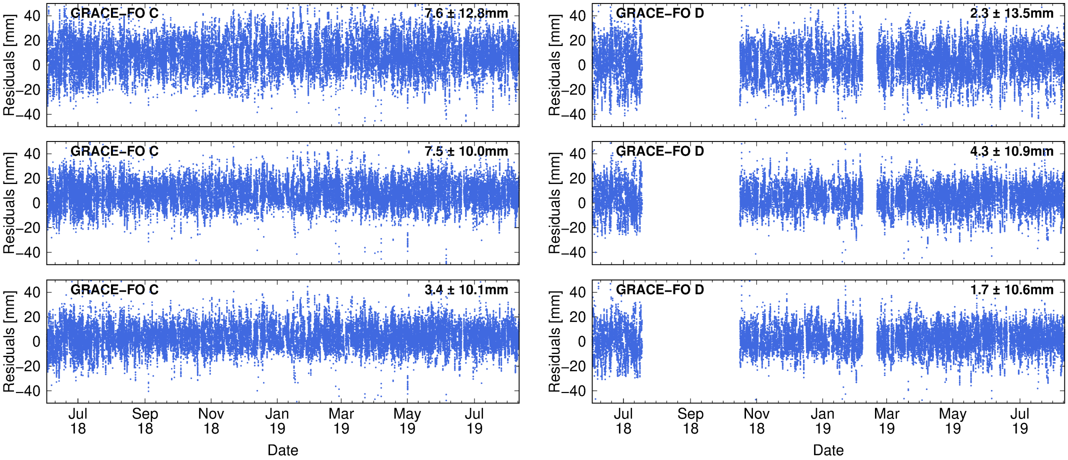
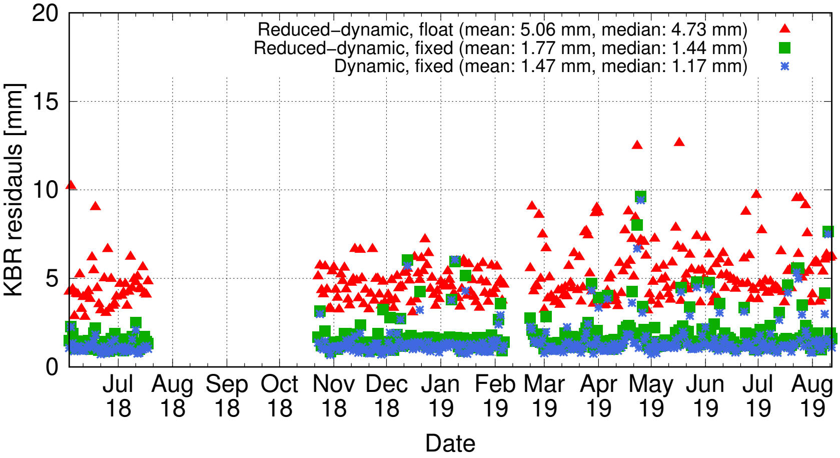


Noticeable offset for reduced-dynamic orbits, more pronounced for GRACE-FO C.

K-band validation for GRACE-FO

Daily RMS values of K-band range residuals (additional independent validation):



Estimated corrections w.r.t. SLRF2014

Coordinate and range bias corrections from 435 days of dynamic, ambiguity-fixed Swarm-A/B/C, Sentintel-3A/B and GRACE-FO C/D orbits:

Station	SOD	E [mm]	N [mm]	U [mm]	B [mm]
Badary	18900901	8.0 ± 0.6	-0.2 ± 0.6	6.0 ± 2.2	8.4 ± 1.4
Yarragadee	70900513	4.8 ± 0.1	-0.3 ± 0.1	-2.5 ± 0.4	0.6 ± 0.2
Greenbelt	71050725	3.5 ± 0.2	6.2 ± 0.2	-12.7 ± 0.6	-6.3 ± 0.3
Monument Peak	71100412	-2.8 ± 0.2	-7.5 ± 0.2	-10.7 ± 0.9	0.3 ± 0.5
Haleakala	71191402	4.5 ± 0.4	-4.5 ± 0.4	1.2 ± 1.3	11.0 ± 0.8
Papeete	71240802	12.1 ± 0.6	4.5 ± 0.6	-5.1 ± 2.1	-12.8 ± 1.2
Arequipa	74031306	0.2 ± 0.4	3.5 ± 0.4	-4.1 ± 1.4	8.1 ± 0.8
Hartebeesthoek	75010602	-2.7 ± 0.3	6.4 ± 0.3	-6.6 ± 1.0	4.2 ± 0.6
Zimmerwald	78106801	0.8 ± 0.2	2.0 ± 0.2	9.6 ± 0.6	7.6 ± 0.3
Mount Stromlo	78259001	5.9 ± 0.3	2.2 ± 0.2	5.6 ± 0.9	1.6 ± 0.5
Wettzell (SOSW)	78272201	-1.1 ± 0.5	-9.8 ± 0.5	-6.4 ± 1.7	5.7 ± 1.0
Graz	78393402	2.8 ± 0.2	3.3 ± 0.2	8.7 ± 0.7	11.8 ± 0.4
Herstmonceux	78403501	3.2 ± 0.3	1.6 ± 0.3	-4.0 ± 1.0	-2.3 ± 0.6
Potsdam	78418701	1.0 ± 0.3	3.7 ± 0.3	17.0 ± 0.9	-0.7 ± 0.6
Matera	79417701	1.7 ± 0.4	4.8 ± 0.4	4.2 ± 2.0	-5.3 ± 1.0

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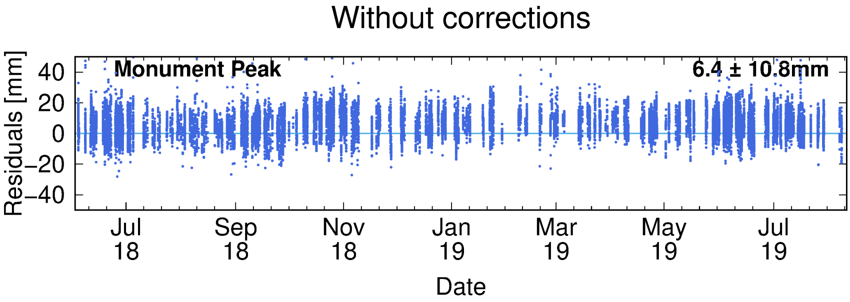
Estimated corrections w.r.t. SLRF2014 (2)

Corrections for station **Monument Peak (71100412)** from different orbit types:

Orbits	E [mm]	N [mm]	U [mm]	B [mm]
Float	-3.3 ± 0.2	-10.5 ± 0.2	-21.8 ± 0.9	-2.5 ± 0.5
Fixed	-3.2 ± 0.2	-7.8 ± 0.2	-12.4 ± 0.9	0.8 ± 0.5
Fixed + NG	-2.8 ± 0.2	-7.5 ± 0.2	-10.7 ± 0.9	0.3 ± 0.5

Reduction of residuals (1)

Monument Peak (71100412), all satellites:



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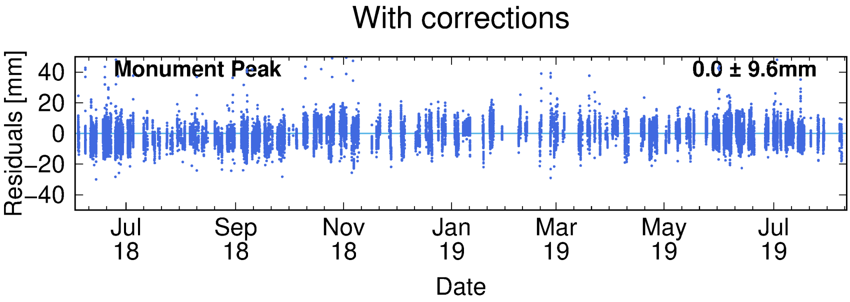
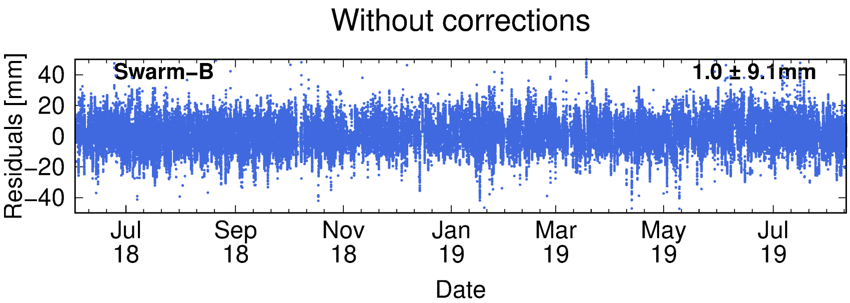


Reduction of residuals (2)



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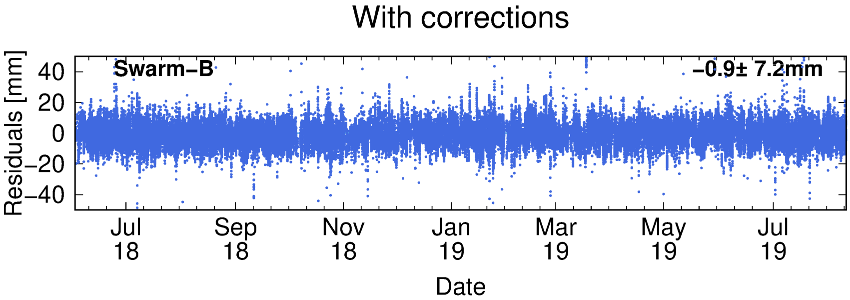

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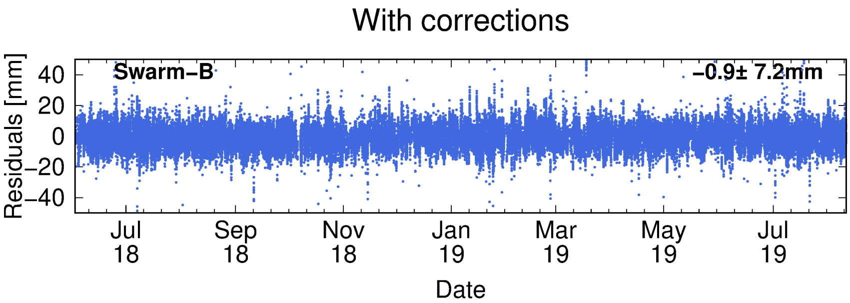

SLR residuals (mean ± std.) of dynamic and ambiguity-fixed orbits with and without corrections:

Orbits	w/o corr.	w/ corr. [mm]
Swarm-A	$+3.1 \pm 9.6$	$+1.0 \pm 7.7$
Swarm-B	$+1.0 \pm 9.1$	-0.9 ± 7.2
Swarm-C	$+2.2 \pm 9.6$	$+0.0 \pm 7.7$
Sentinel-3A	$+1.5 \pm 10.3$	$+0.0 \pm 7.8$
Sentinel-3B	$+1.1 \pm 10.2$	-0.7 ± 7.4
GRACE-FO C	$+3.4 \pm 10.1$	$+1.7 \pm 7.9$
GRACE-FO D	$+1.7 \pm 10.6$	$+0.0 \pm 8.3$

Conclusion

- SLR to LEO satellites not only sensitive to radial, but also to 3-dimensional orbit errors, as well as station positions and range (and timing) biases.
- Dynamic ambiguity-fixed LEO orbits have reached a quality level that is interesting to validate/calibrate the SLR station network. Needs good knowledge of satellite geometry (antenna and reflector locations).
- Station parameter corrections sometimes at 1 cm level even for high-performance SLR stations.
- Corrections remove mean offsets in SLR residuals for individual stations and reduces standard deviation.
- Kinematic orbits profit a lot from ambiguity fixing. SLR now sees hardly any differences to the (superior) dynamic orbits.

- For methodology and further results, see

  Arnold D., Montenbruck O., Hackel S., Sosnica K. (2019): Satellite Laser Ranging to Low Earth Orbiters: Orbit and Network Validation, Journal of Geodesy, 93(11), 2315-2334, doi:10.1007/s00190-018-1140-4

- For CODE's phase bias products, see `ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT`

Thank you for your attention!