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Millimeter-accuracy SLR bias determination using independent multi-LEO DORIS and GNSS-based orbits

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Motivation (1)

- Satellite Laser Ranging (SLR) has become an invaluable core technique in numerous geodetic applications, e.g., ITRF realizations or validation of microwave-based orbits of active satellites.
- Inherent short-time precision of SLR observations considered to be at a few mm level.
- However, numerous SLR stations show **non-negligible biases**
  - → For SLR orbit validation one often restricts to a subset of high-performing stations considered to have negligible biases
- Reducing SLR systematic errors is mandatory to use SLR as an orbit drift monitoring tool (e.g., for satellite altimetry we aim for 1 mm RMS short-term accuracy and 0.1 mm/y long-term stability).

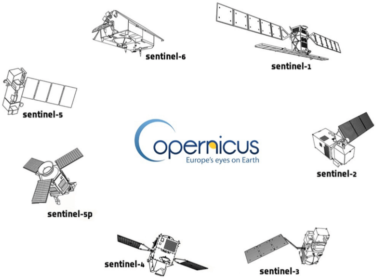
Motivation (2)

- In recent years, microwave-based (GNSS, DORIS) orbits of satellites in Low Earth Orbit (LEO) have reached generally very high qualities (e.g., due to carrier phase ambiguity fixing and advances in dynamical modeling).
- SLR measurements to active LEO satellites are less prone to satellite signature effects.

⟹ **We aim to show that SLR residual analysis for active LEO satellites can serve as interesting source for SLR station calibrations, e.g., of range biases.**

  - Analyze SLR residuals to numerous LEO satellites → less prone to geographically correlated orbit errors.
  - Intercomparison with three different processing software packages.
  - Study initiated by members of the Copernicus Precise Orbit Determination (POD) Quality Working Group (QWG).

Copernicus POD QWG



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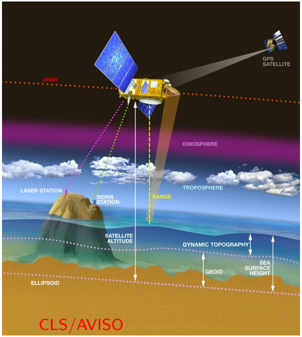
The Copernicus POD QWG is a consortium of different institutions with the purpose of supporting the POD of the European Copernicus Sentinel satellites by cross-validation and intercomparison.

Contributions

- AIUB
  - GPS-only solutions for Sentinel-3A/B, Swarm-A/B/C and GRACE-FO C/D
  - Bernese GNSS Software
- CNES/CLS
  - DORIS-only and DORIS+GPS solutions for Sentinel-3A/B, CryoSat-2, Saral/AltiKa, Jason-2/3
  - ZOOM
- PosiTim
  - Combinations of QWG solutions for Sentinel-3A/B (GPS/DORIS)
  - Napeos
- In the future: add contributions from DLR (GHOST processing software), exchange started.

Methods

- Analysis is done entirely on the level of SLR residuals to orbits generated by other means (i.e., no orbit adjustment using SLR data) → “lightweight” computations.
- Selected station-related parameters are estimated to minimize residuals over multiple missions.
- Focus here: Determination and comparison of annual SLR station biases for 2016-2019.
- Further details on methodology: see DOI 10.1007/s00190-018-1140-4

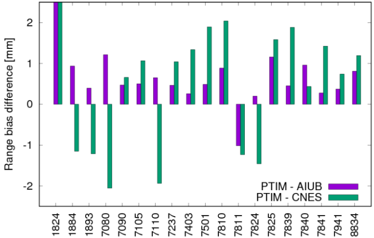


CLS/AVISO

First steps

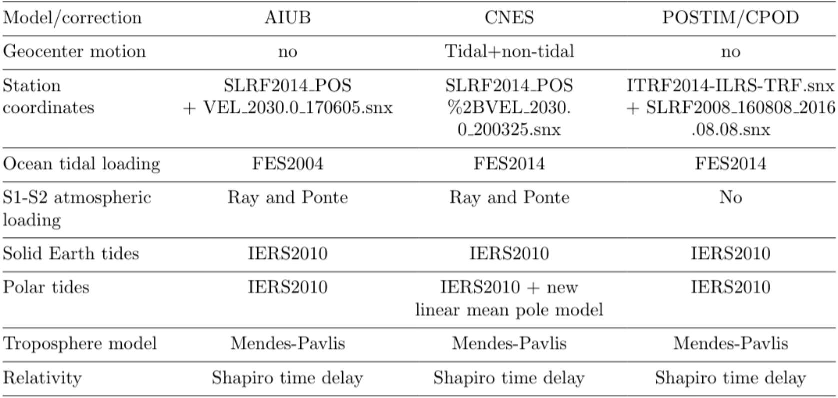
Among three ACs:

- Agree on/check processing setup (CoM, offsets, LRR corrections), based on analysis of combined Sentinel-3A orbits of June 2017, comparison of SLR residuals
- Comparison of SLR measurement corrections (non-tidal loading corrections discarded)
  → Sub-mm agreement (after some bug fixing), except for ocean loading and pole tide modeling
- Comparison of monthly range bias estimates based on single Sentinel-3A combined orbits of June 2017



Differences of estimated range biases for S3A and June 2017. Up to 2 mm differences due to choice of mean pole model.

SLR measurement corrections



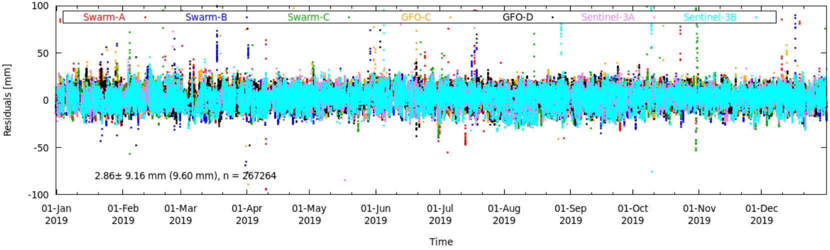
Model/correction	AIUB	CNES	POSTIM/CPOD
Geocenter motion	no	Tidal+non-tidal	no
Station coordinates	SLRF2014_POS + VEL_2030.0_170605.snx	SLRF2014_POS %2BVEL_2030.0_200325.snx	ITRF2014-ILRS-TRF.snx + SLRF2008_160808_2016.08.08.snx
Ocean tidal loading	FES2004	FES2014	FES2014
S1-S2 atmospheric loading	Ray and Ponte	Ray and Ponte	No
Solid Earth tides	IERS2010	IERS2010	IERS2010
Polar tides	IERS2010	IERS2010 + new linear mean pole model	IERS2010
Troposphere model	Mendes-Pavlis	Mendes-Pavlis	Mendes-Pavlis
Relativity	Shapiro time delay	Shapiro time delay	Shapiro time delay

Example (1)

- Ambiguity-fixed and dynamic GPS-based LEO orbit solutions for Sentinel-3, Swarm and GRACE-FO (7 satellites) by AIUB for 2019
- Bernese GNSS Software (POD and SLR validation)
- SLR residuals: 20 cm outlier threshold, 10 deg elevation cutoff
- Estimate **annual range biases and station coordinate corrections**
- 32 SLR stations involved in tracking

Example (2)

Consider only residuals for 11 high performing ILRS stations with many data and high precision:

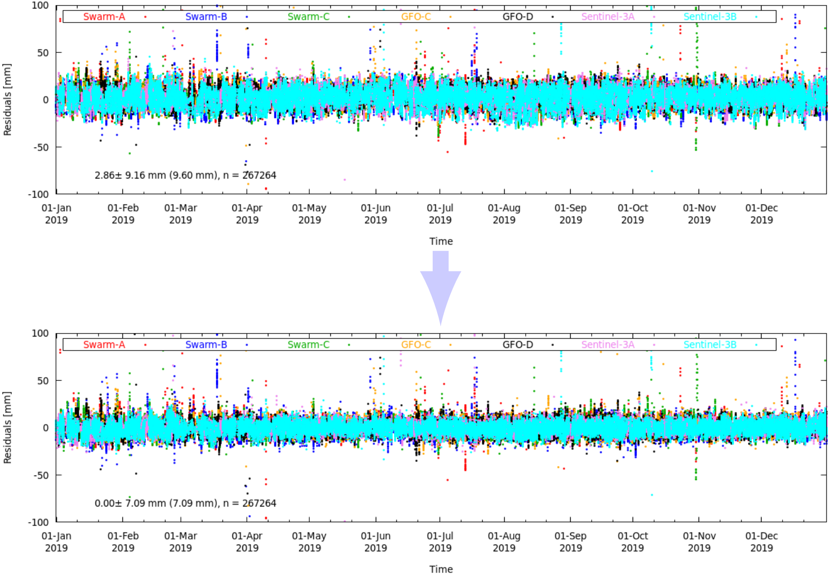


Example (3)

Coordinate and range bias corrections from residual analysis:

Station	SOD	E [mm]	N [mm]	U [mm]	B [mm]
Yarragadee	70900513	4.9 ± 0.1	-0.5 ± 0.1	-2.1 ± 0.4	2.7 ± 0.2
Greenbelt	71050725	3.6 ± 0.2	6.4 ± 0.2	-13.6 ± 0.6	-6.9 ± 0.3
Monument Peak	71100412	-4.0 ± 0.3	-8.6 ± 0.3	-13.7 ± 1.0	0.2 ± 0.5
Haleakala	71191402	4.9 ± 0.4	-4.0 ± 0.4	-1.5 ± 1.3	9.9 ± 0.7
Hartebeesthoek	75010602	-2.5 ± 0.3	3.9 ± 0.3	-5.1 ± 1.2	2.6 ± 0.7
Zimmerwald	78106801	1.0 ± 0.2	2.0 ± 0.2	6.9 ± 0.7	8.6 ± 0.3
Mount Stromlo	78259001	6.8 ± 0.2	2.0 ± 0.2	6.4 ± 0.8	1.7 ± 0.5
Graz	78393402	2.7 ± 0.3	3.5 ± 0.2	6.8 ± 0.7	12.7 ± 0.4
Herstmonceux	78403501	3.8 ± 0.3	1.2 ± 0.3	-5.7 ± 1.0	-2.2 ± 0.7
Potsdam	78418701	1.8 ± 0.3	2.8 ± 0.4	14.2 ± 1.0	-1.3 ± 0.7
Matera	79417701	2.4 ± 0.5	4.5 ± 0.5	-4.9 ± 2.8	-7.8 ± 1.4

Example (4)


Swarm-A
Swarm-B
Swarm-C
GFO-C
GFO-D
Sentinel-3A
Sentinel-3B
Residuals [mm]
100
50
0
-50
-100
2.86± 9.16 mm (9.60 mm), n = 267264
01-Jan 2019
01-Feb 2019
01-Mar 2019
01-Apr 2019
01-May 2019
01-Jun 2019
01-Jul 2019
01-Aug 2019
01-Sep 2019
01-Oct 2019
01-Nov 2019
01-Dec 2019
Time
0.00± 7.09 mm (7.09 mm), n = 267264

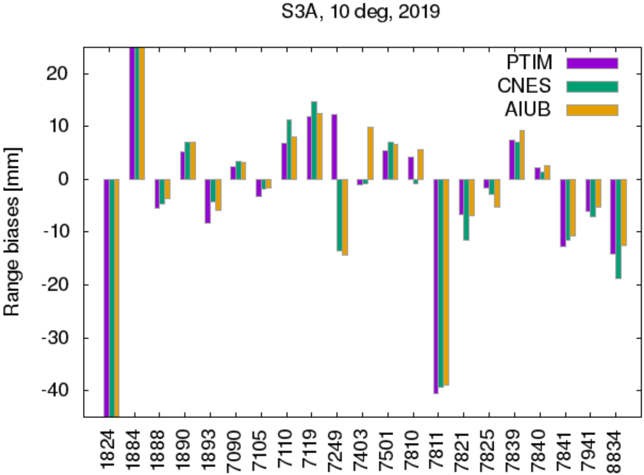
Estimation of independent yearly biases

How robust are such results?

- AIUB, CNES/CLS and PosiTim independenty estimated annual station parameters using their different sets of LEO satellites and analysis softwares.
- Different elevation cutoff angles were tested (10, 30 and 50 degrees)
- Different sets of parameters were tested:
  1. SLR station range biases
  2. SLR station range biases + SLR station height component
  3. SLR station range biases + SLR station coordinates

Elevation cutoff

Range bias estimates for 2019 based on S3A orbits and different elevation cutoffs:



Elevation cutoff

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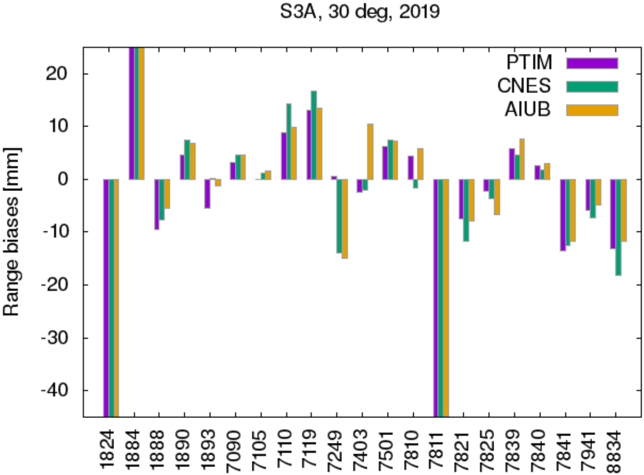

Elevation cutoff

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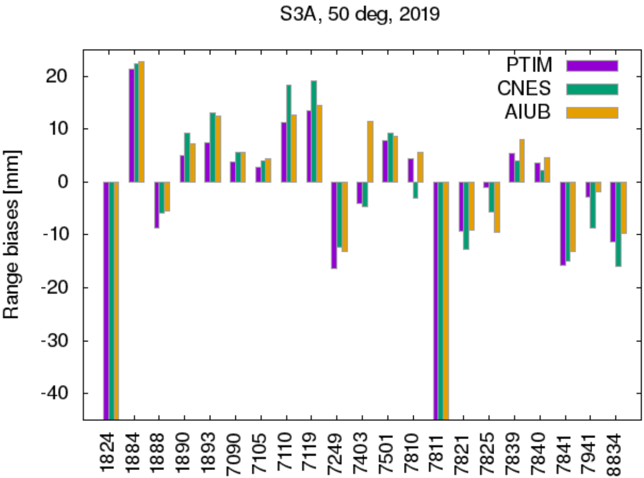
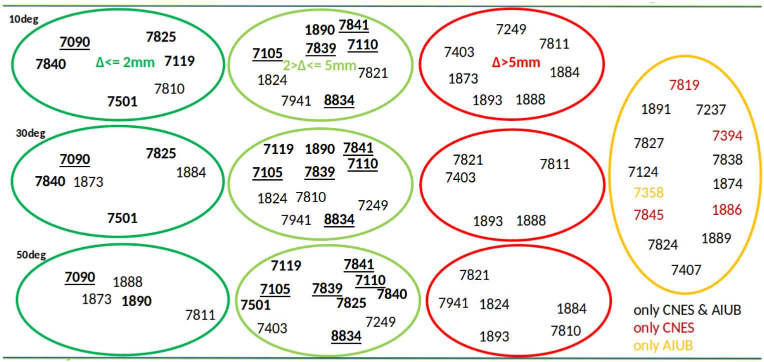


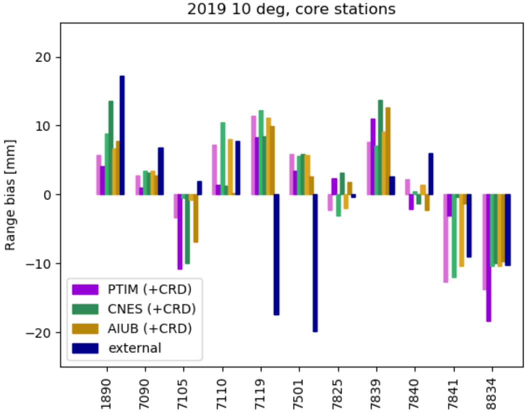
Station clustering: Range biases only

Clusters of stations for which the three range bias estimates agree on different levels Δ for 2019 and all satellites. Bold stations: For all elev. cutoff angles either in cluster 1 or 2. Underlined stations: For all elev. cutoff angles in same cluster.



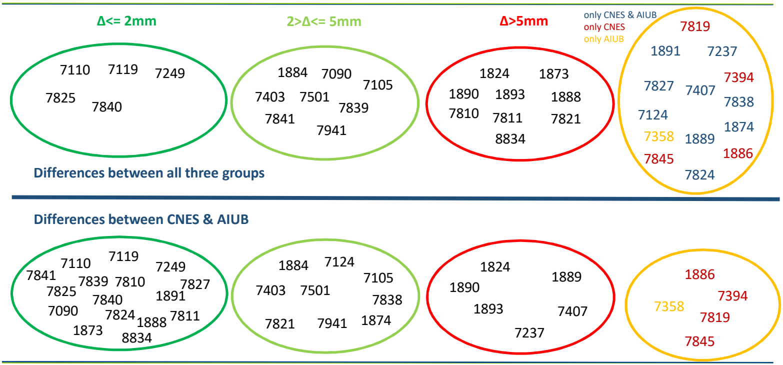
Estimating also station coordinates

Estimated range biases for 2019 and all satellites. Light color: Only range bias estimated. Dark color: Range bias and coordinates estimated. External: Range biases from T. Otsubo (SLR sats.).



Station clustering: Range biases + CRD

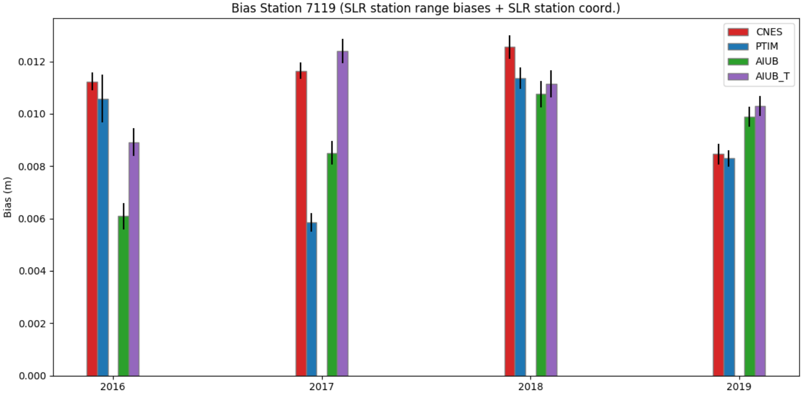
Clusters of stations for which the range bias estimates agree on different levels Δ for 2019, all satellites and 10 degree elevation cutoff.



AIUB and CNES agree for 16 stations on range biases within 2 mm (recall: PosiTim estimates based only on S3A/B)!

Range bias stability

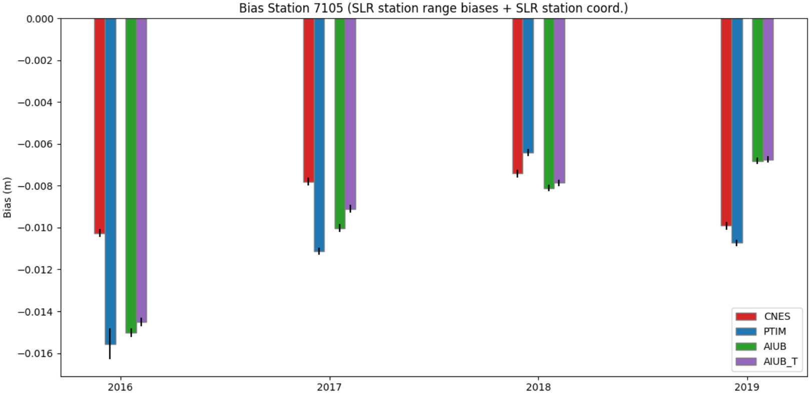
$\Delta \leq 2$ mm (2019)



AIUB_T: Estimating in addition timing offset

Range bias stability

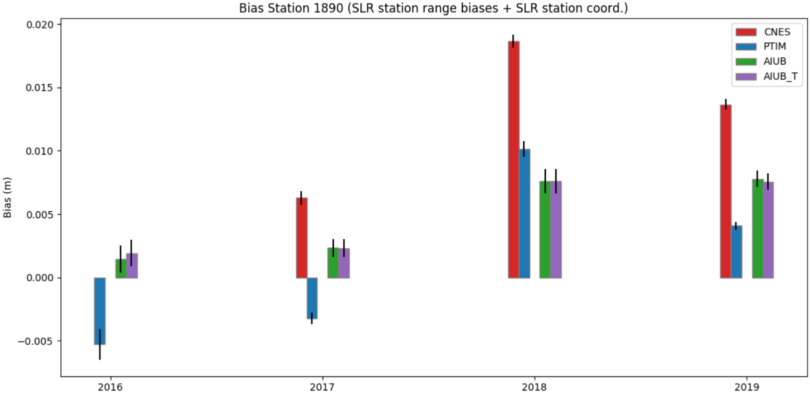
$2 > \Delta \leq 5$ mm (2019)



AIUB_T: Estimating in addition timing offset

Range bias stability

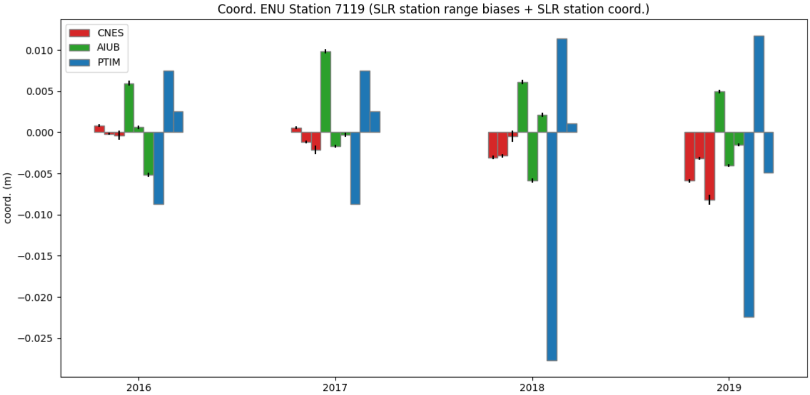
$\Delta > 5$ mm (2019)



AIUB_T: Estimating in addition timing offset

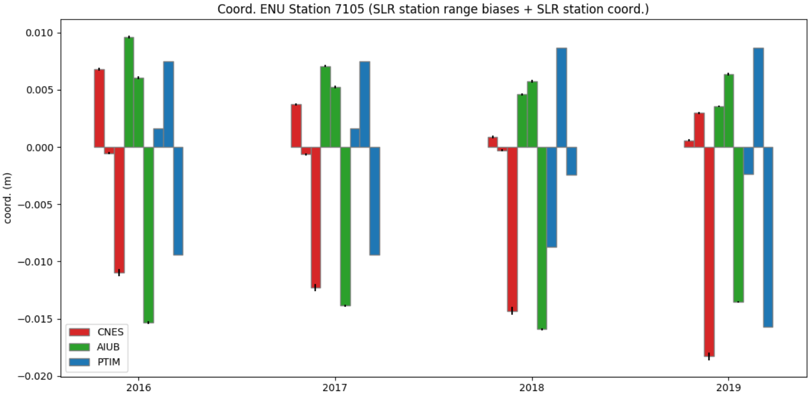
Station coordinates

Estimated coordinate corrections in East, North and Up direction.
$\Delta \leq 2$ mm (2019)



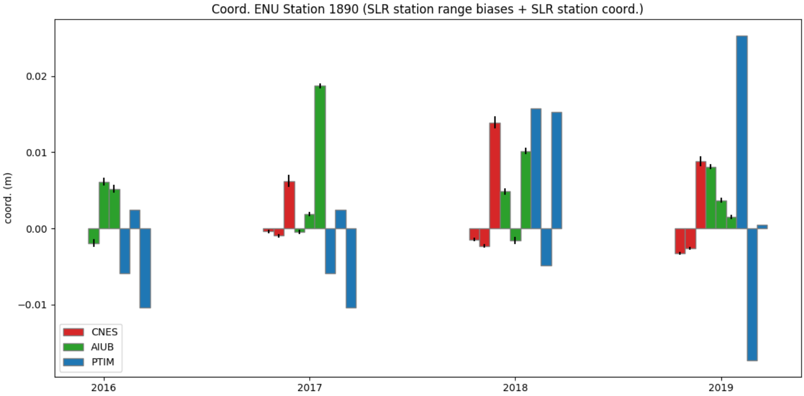
Station coordinates

Estimated coordinate corrections in East, North and Up direction.
$2 > \Delta \leq 5$ mm (2019)


Coord. ENU Station 7105 (SLR station range biases + SLR station coord.)

Station coordinates

Estimated coordinate corrections in East, North and Up direction.
$\Delta > 5$ mm (2019)



Conclusions

- For a significant number of stations estimated range biases closer than 5 mm or even 2 mm, even though using different/independent orbit solutions (and software packages).
- Better consistency when estimating also station coordinates.
- Using multiple LEO missions for analysis seems to mostly mitigate geographically correlated orbit errors.
- These kind of analyses constitute an interesting source of information for SLR station bias calibrations.

Next steps

- Even though the usage of differently generated orbit products underlines the robustness of the estimated parameters, this compares different reference frame realizations and complicates the interpretation in particular of estimated coordinate corrections ⟶ started to perform systematic tests based on one common orbit set.
- Even in multi-mission analyses systematic orbit errors could deteriorate the station parameter estimations. The simultaneous estimation of orbit correction parameters might help, but requires parameter constraints ⟶ exchange and first tests with DLR.
- Towards a new ILRS product?