

Systematic errors in Satellite Laser Ranging validations of microwave-based low Earth orbit solutions

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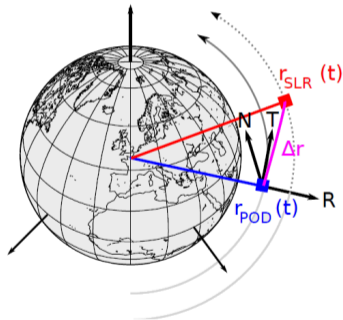
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European
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Introduction (1)

- Satellite Laser Ranging (SLR) is a **core technique** in many geodetic applications.
- SLR measurements to active Low Earth Orbiters (LEOs) mainly used as **independent validation tool** for microwave-based (GNSS/DORIS) orbits
 - Analysis of 3D orbit errors.



- Wide range of observation qualities among stations of the International Laser Ranging Service (ILRS), numerous **non-negligible biases**.

Introduction (2)

- Biases will affect SLR validation results → reliability (e.g., for altimetry missions)?
→ Restriction to subset of stations with small biases?

GGOS requirements on terrestrial reference frame (Plag and Pearlman, 2009)

- Accuracy: 1 mm
 - Stability: 0.1 mm/yr
-
- Short-time precision of SLR observations at few mm level, but
 - Systematic errors / biases are a major obstacle towards fully exploiting SLR measurement accuracies for geodetic applications.

Introduction (3)

- Microwave-based LEO orbits 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** (broadening of returned signal due to reflection from multiple cube corner reflectors).
- Many SLR observations to active LEOs!



Laser retroreflector on Sentinel-3

Goal

Use SLR observations to multiple active LEOs to investigate systematic measurement errors.

Methods

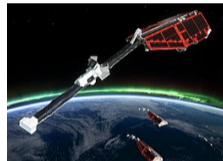
- GNSS processing: Produce state-of-the-art dynamic orbit solutions for multiple LEO missions (to lower impact of geographically correlated orbit errors).



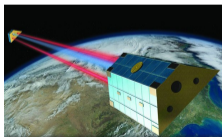
Sentinel-3A/B



Sentinel-6A



Swarm-A/B/C



GRACE-FO C/D

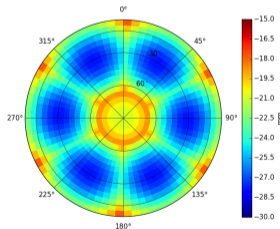


Jason-3

- 9 LEOs
- Undifferenced GNSS processing with carrier phase ambiguity fixing using CODE GNSS products & Bernese GNSS Software
- Sentinel-6A: GPS + Galileo

Methods

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- Introduce microwave-based LEO orbits as fixed and compute SLR residuals (observed minus computed range) based on
 - known LEO satellite orbit, attitude, geometry, reflector characteristics



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Arnold et al. (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

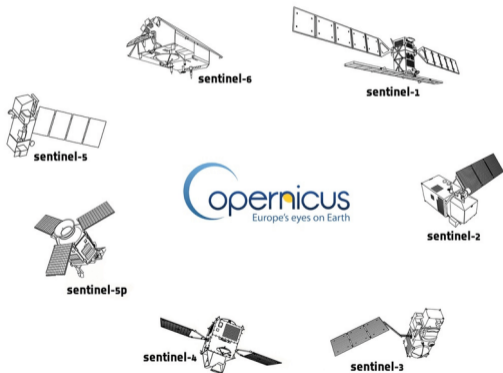
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- Compute partials of range measurements w.r.t. parameters to estimate (e.g., station range or timing biases, coordinate corrections, ...)
- Form and solve normal equations to minimize residuals for considered satellites and time span.

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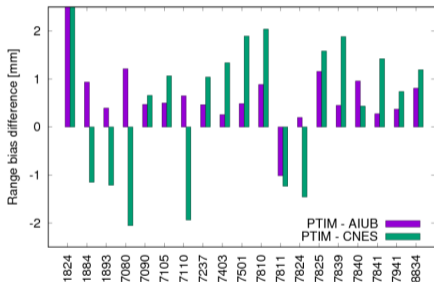
Copernicus POD QWG Bias Study (1)

- In the frame of the Copernicus Precise Orbit Determination (POD) Quality Working Group (QWG), a study was initiated, to address SLR station biases and their determination from residual analysis to active LEOs.



Copernicus POD QWG Bias Study (2)

- AIUB, CNES/CS-SI, PosiTim (3 independent analysis software packages and sets of orbit solutions), later also DLR
- First steps: Software and model comparisons.

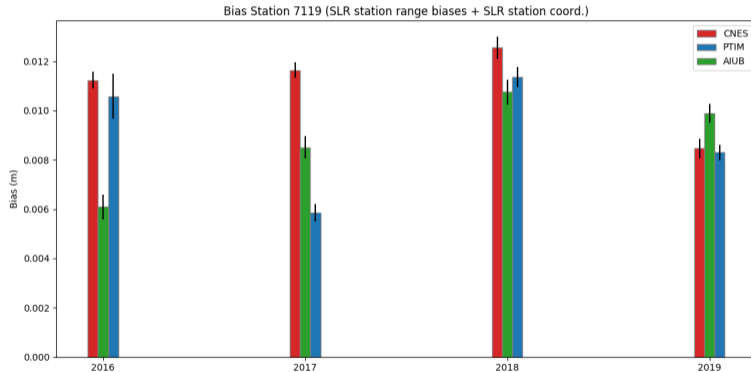


Differences of estimated range biases for June 2017, based on a single set of Sentinel-3A orbit. Up to 2 mm differences due to choice of mean pole model.

- Then estimation of yearly range biases for 2016-2019 using independent orbit sets.
- Testing different elevation cutoffs and co-estimation of station coordinates.

Copernicus POD QWG Bias Study (3)

Yearly range bias estimates for station Haleakala, Hawaii (coordinates co-estimated),



Good agreement of biases, in particular when co-estimating station coordinate corrections.

Publication on the way.

What about orbit errors?

Station errors

- Range biases
- Coordinate errors
- Timing biases
- Troposphere-related errors
- Distance-dependent errors
- ...

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Orbit errors

- Incorrect CoM location
- Incorrect offset vectors (microwave sensors, laser reflector)
- deficiencies in force models
- ...

Orbit errors (1)

Orbit offsets estimated for June 2021 based on 11 high-performing stations (no station parameters estimated):

Satellite	dR [mm]	dT [mm]	dN [mm]	
Jason-3	-0.1	12.9	0.5	
Swarm-A	5.3	-2.3	-3.5	
Swarm-B	0.4	-2.5	0.5	
Swarm-C	3.8	-3.0	-3.1	dR: Radial
GFO-C	4.1	-7.0	-3.4	dT: Along-track
GFO-D	5.4	-5.1	-2.1	dN: Cross-track
Sentinel-3A	3.4	-1.0	-2.0	
Sentinel-3B	2.1	0.9	1.7	
Sentinel-6A	1.1	-0.6	-2.0	

Orbit errors (2)

Experiment: Take these offsets for granted and shift orbits accordingly. Redo SLR analysis (including screening, so slightly different obs.):

Satellite	dR [mm]	dT [mm]	dN [mm]
Jason-3	-0.0	0.5	-0.2
Swarm-A	-0.0	0.2	-0.1
Swarm-B	-0.0	0.0	0.0
Swarm-C	-0.1	0.1	0.0
GFO-C	-0.5	-0.4	-0.1
GFO-D	0.3	-0.3	0.2
Sentinel-3A	0.0	-0.6	0.2
Sentinel-3B	0.0	0.0	0.0
Sentinel-6A	0.0	-0.1	0.1

How will these shifted orbits influence station parameters?

Sensitivity to orbit errors (1)

Station parameters for June 2021 estimated based on “true” orbits:

Station	ID	dE [mm]	dN [mm]	dU [mm]	dr [mm]	dt [μ s]
Svetloe	1888	2.0	1.7	-5.6	-3.2	0.6
Badary	1890	4.0	3.7	16.2	28.5	-0.5
Irkutsk	1891	8.2	12.2	1.3	-2.9	-0.7
Katzively	1893	4.1	-22.1	-73.5	-44.4	0.6
Yarragadee	7090	3.3	-8.9	-6.6	0.1	-0.1
Greenbelt	7105	1.4	2.2	-16.8	-7.5	0.2
Monument Peak	7110	-5.1	-10.1	-11.0	-5.5	-0.1
Changchun	7237	2.3	-15.6	67.4	16.0	1.2
Zimmerwald	7810	-0.1	-1.1	5.9	3.9	-0.0
Mt Stromlo	7825	5.8	-0.2	-1.0	-2.6	0.2
Simosato	7838	22.2	-17.9	-43.3	-10.7	-0.5
Graz	7839	0.2	1.0	-2.4	3.3	0.4
Herstmonceux	7840	0.2	-0.8	-1.2	-1.6	0.3
Matera	7941	-0.9	4.8	3.6	-5.5	0.0
Wetzell (WLRS)	8834	-10.2	-6.8	-6.2	-1.5	1.3

(dE,dN,dU): Crd. corr.

dr: Range bias

dt: Timing bias

Ex. for obs. numbers and formal errors:

	Matera	Yarragadee
nObs	740	10'297
δ dE	1.4 mm	0.3 mm
δ dN	1.3 mm	0.3 mm
δ dU	5.5 mm	1.1 mm
δ dr	3.0 mm	0.5 mm
δ dt	0.24 μ s	0.05 μ s

Notice: Only a selection of stations shown

Sensitivity to orbit errors (2)

Station parameters for June 2021 estimated based on “shifted” orbits:

Station	ID	dE [mm]	dN [mm]	dU [mm]	dr [mm]	dt [μ s]
Svetloe	1888	3.8	1.4	-2.9	-2.1	0.3
Badary	1890	5.9	1.8	16.1	26.0	-0.9
Irkutsk	1891	14.1	12.8	5.9	-0.1	-1.4
Katzively	1893	4.4	-21.0	-68.3	-43.8	0.7
Yarragadee	7090	4.3	-8.6	-6.2	-1.1	-0.1
Greenbelt	7105	1.1	3.2	-16.5	-9.0	0.3
Monument Peak	7110	-3.3	-11.0	-8.9	-5.6	-0.2
Changchun	7237	0.9	-10.7	69.8	15.2	1.1
Zimmerwald	7810	1.5	-0.3	7.2	3.3	0.0
Mt Stromlo	7825	6.7	-0.1	1.5	-2.1	0.3
Simosato	7838	21.8	-21.0	-42.4	-13.9	0.3
Graz	7839	1.4	1.4	-0.9	2.7	0.3
Herstmonceux	7840	1.1	-1.1	-0.6	-2.5	0.3
Matera	7941	-0.0	4.4	3.1	-6.6	0.1
Wetzell (WLRS)	8834	-4.9	-4.3	-11.0	-6.4	1.5

(dE,dN,dU): Crd. corr.

dr: Range bias

dt: Timing bias

Ex. for obs. numbers and formal errors:

	Matera	Yarragadee
nObs	740	10'310
δ dE	1.4 mm	0.3 mm
δ dN	1.3 mm	0.3 mm
δ dU	5.5 mm	1.1 mm
δ dr	3.0 mm	0.5 mm
δ dt	0.24 μ s	0.05 μ s

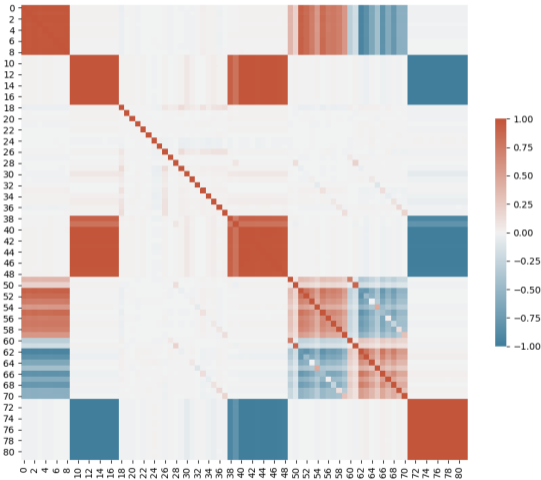
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Correlations

Ideally, we should estimate both station- and orbit-related parameters together. But...

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Estimated parameters (9 LEOs, 11 stations):

- 0-8: Radial orbit offsets
- 9-17: Along-track orbit offsets
- 18-26: Cross-track orbit offsets
- 27-37: N station coord. corrections
- 38-48: E station coord. corrections
- 49-59: U station coord. corrections
- 60-70: Range biases
- 71-81: Timing biases

High correlations:

- Radial orbit offsets & Up coord.
- Radial orbit offsets & Range biases
- Along-track orbit offsets & East coord.
- Along-track orbit offsets & Timing biases
- ...

Impact of constraints

Use **constraints** to decorrelate parameters. Impact on yearly station parameters for station Zimmerwald for 2021:

	dE [mm]	dN [mm]	dU [mm]	dr [mm]	dt [μ s]
No orbit parameters estimated	-1.8	1.5	8.1	4.3	-0.1
Zero-mean of station U crd.	-0.4	1.3	6.3	4.9	-0.2
Zero-mean of R orb. offsets	-0.4	1.3	7.8	4.2	-0.2
NNT constr.	-0.4	1.3	9.9	3.3	0.0
NNT constr. (*)	-0.3	1.1	2.0	7.2	-0.1
NNT+NNR constr.	-0.5	1.3	7.5	4.5	0.0
NNT+NNR constr. (*)	-0.8	1.1	4.3	5.7	0.4
NNT+NNR+NNS constr.	-0.4	1.3	5.0	5.6	0.0
NNT+NNR+NNS constr. (*)	-0.8	1.1	2.4	6.6	0.4

(*): Excluding stations with large residuals in Helmert transformations

Notice: In all cases with estimated orbit parameters, a zero-mean constraint for the timing biases was applied in addition (to decorrelate with along-track orbit offsets).

2019-2021 (1)

Yearly station parameters 2019-2021 when estimating orbit parameters with zero-mean constraint for R orbit offsets and for station timing biases:

Greenbelt:

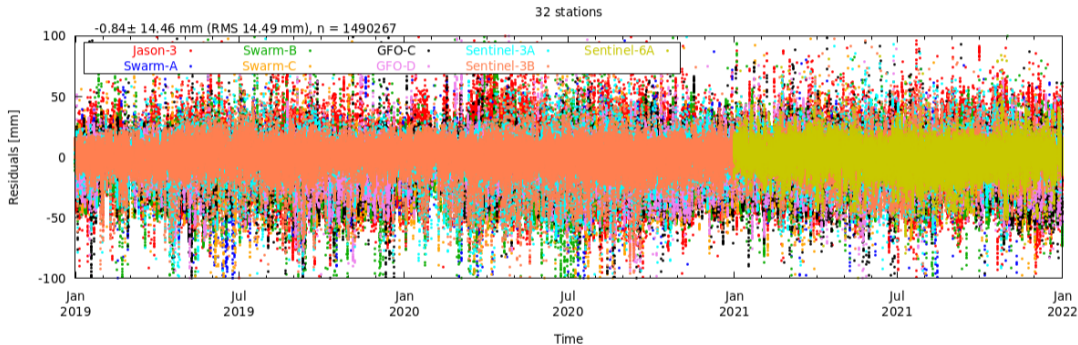
	dE [mm]	dN [mm]	dU [mm]	dr [mm]	dt [μ s]
2019	3.2	5.9	-12.3	-7.0	0.0
2020	3.7	6.3	-11.0	-5.1	-0.1
2021	2.9	6.3	-12.8	-2.8	0.0

Arkhyz:

	dE [mm]	dN [mm]	dU [mm]	dr [mm]	dt [μ s]
2019	20.9	-11.2	-168.9	-104.7	0.9
2020	18.2	-18.1	-192.5	-118.1	0.2
2021	16.8	-20.6	-177.4	-104.9	0.3

2019-2021 (2)

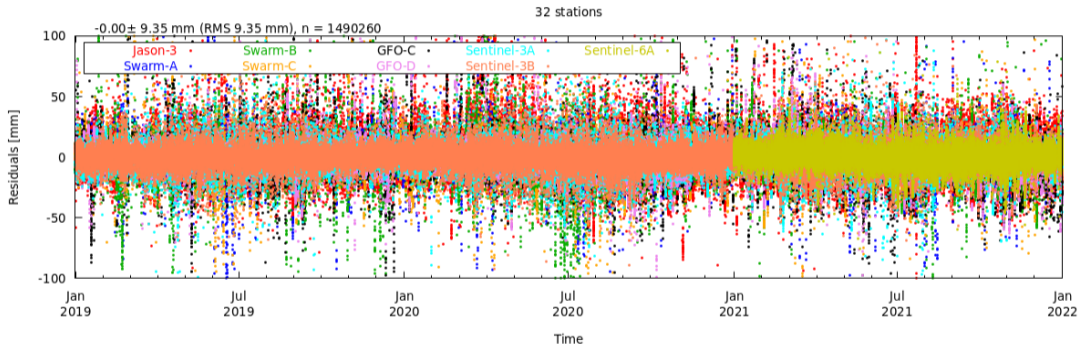
Residuals for 32 stations, 9 LEOs before adjustment:



RMS: 14.49 mm

2019-2021 (3)

Residuals for 32 stations, 9 LEOs after adjusting yearly orbit offsets and station par.:



RMS: 9.35 mm

Conclusions

- Microwave-based orbits for active LEOs are often of very good quality.
- The numerous SLR observations to these LEOs have then the potential to be used for the determination, monitoring and calibration of systematic station errors.
- Systematic orbit errors affect the results and should be taken into account.
- When co-estimating them, constraints are needed for decorrelation.
- Further investigations/discussions needed to find the most “appropriate” constraints.
- Think about using SLR observations to active LEOs in reference frame realizations...

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Thank you for your attention!