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

D. Arnold[1] A. Couhert[2] O. Montenbruck[3] C. Kobel[1] E. Saquet[2,4]
H. Peter[5] F. Mercier[2] A. Jäggi[1]

[1] Astronomical Institute, University of Bern, Switzerland
[2] Centre National d'Etudes Spatiales, Toulouse, France
[3] Deutsches Zentrum für Luft- und Raumfahrt, Wessling, Germany
[4] Collecte Localisation Satellites, Toulouse, France
[5] PosiTim UG, Seeheim-Jugenheim, Germany

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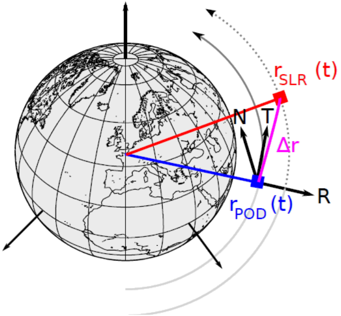
Introduction (1)

- 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).

Laser retroreflector on Sentinel-3

- Many SLR observations to active LEOs!

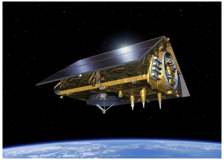
Goal

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

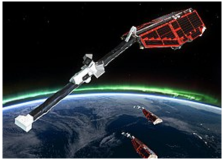
Methods

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

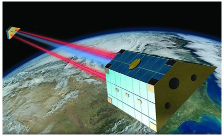
Sentinel-3A/B



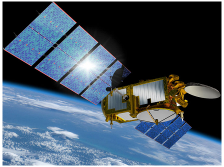
Sentinel-6A



Swarm-A/B/C



GRACE-FO C/D

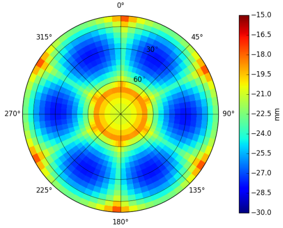


Jason-3

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

Methods

- GNSS processing: Produce state-of-the-art dynamic orbit solutions for multiple LEO missions (to lower impact of geographically correlated orbit errors).
- 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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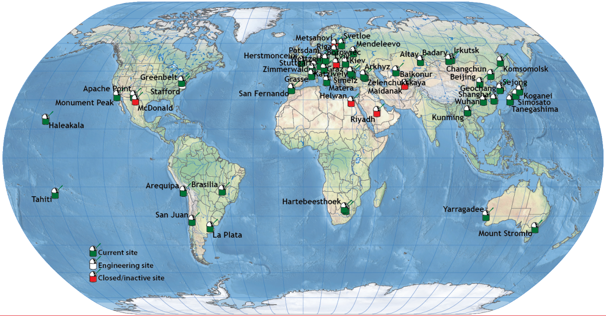
  - known station locations (SLRF2014)



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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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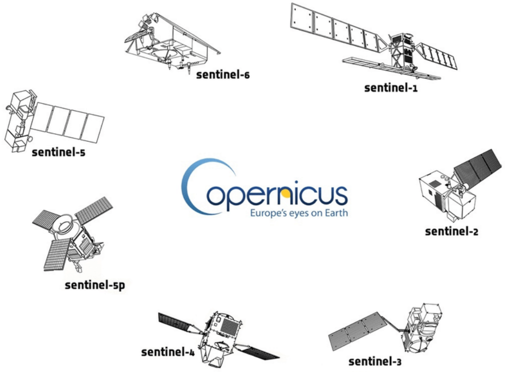
Copernicus POD QWG Bias Study (1)

- 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.



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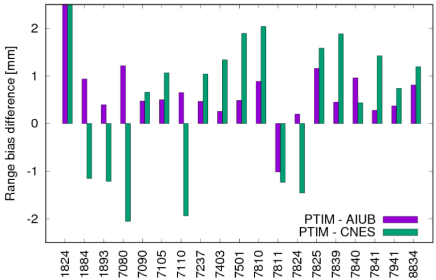
DEUTSCHES GEOFORSCHUNGSZENTRUM

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.

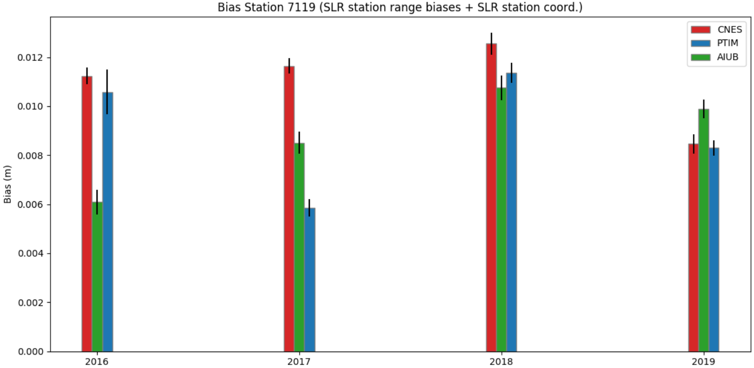


Differences of estimated range biases for June 2017, based on a single set of Sentinel-3A orbit. Up to 2 mm differences due to choice of mean pole model.

- 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
GFO-C	4.1	-7.0	-3.4
GFO-D	5.4	-5.1	-2.1
Sentinel-3A	3.4	-1.0	-2.0
Sentinel-3B	2.1	0.9	1.7
Sentinel-6A	1.1	-0.6	-2.0

dR: Radial
dT: Along-track
dN: Cross-track

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 [μs]
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
Wettzell (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
δdE	1.4 mm	0.3 mm
δdN	1.3 mm	0.3 mm
δdU	5.5 mm	1.1 mm
δdr	3.0 mm	0.5 mm
δdt	0.24 μs	0.05 μs

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 [μs]
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
Wettzell (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
δdE	1.4 mm	0.3 mm
δdN	1.3 mm	0.3 mm
δdU	5.5 mm	1.1 mm
δdr	3.0 mm	0.5 mm
δdt	0.24 μs	0.05 μs

Notice: Only a selection of stations shown

Correlations

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

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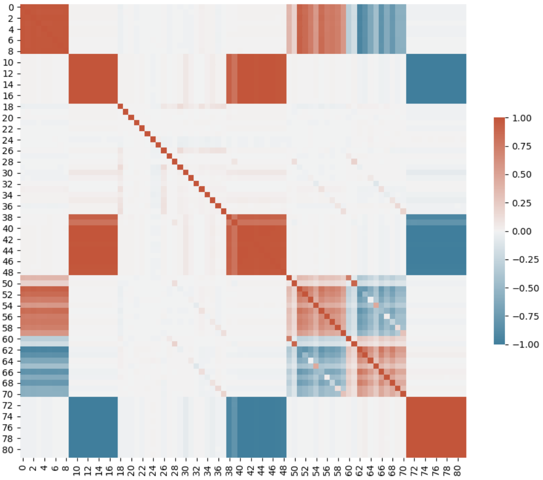


Estimated parameters (9 LEOs, 11 stations):

- 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 [μs]
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:

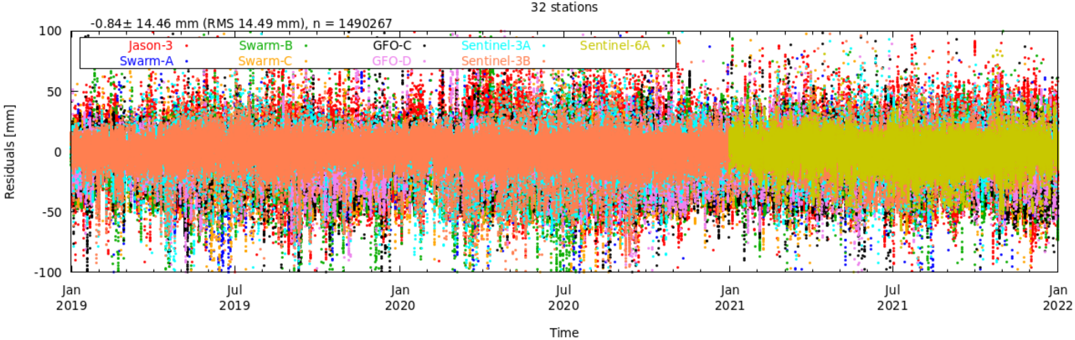
	dE [mm]	dN [mm]	dU [mm]	dr [mm]	dt [μs]
2019	3.2	5.9	-12.3	-7.0	0.0
2020	3.7	6.3	-11.0	-5.1	-0.1
2021	2.9	6.3	-12.8	-2.8	0.0

Arkhyz:

	dE [mm]	dN [mm]	dU [mm]	dr [mm]	dt [μs]
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)

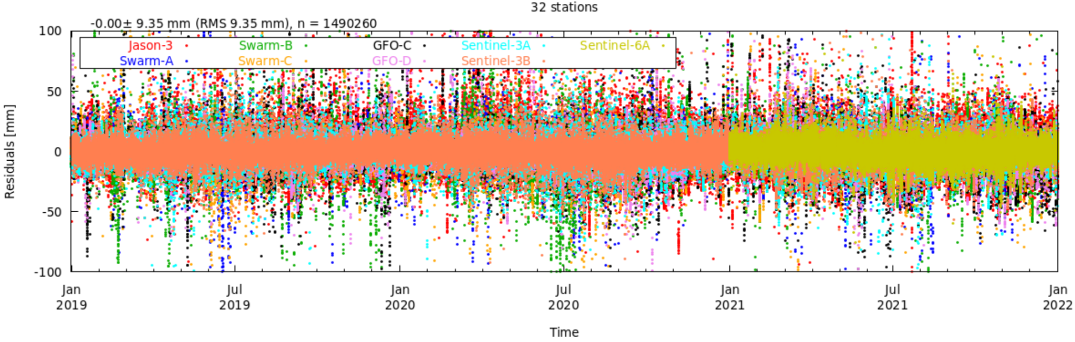
Residuals for 32 stations, 9 LEOs before ajustment:



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" constaints.
- Think about using SLR observations to active LEOs in reference frame realizations...

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Thank you for your attention!