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

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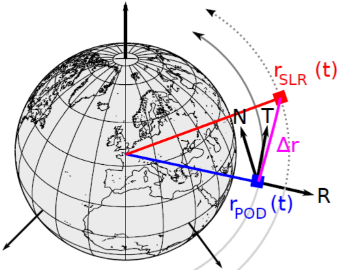
Introduction (1)

- 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.



(Hackel et al., 2015)

- 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

- 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

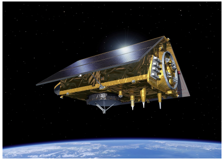
Goal

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

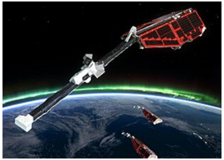
Methods

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

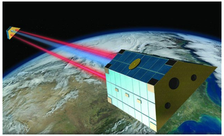
Sentinel-3A/B



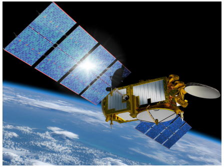
Sentinel-6A



Swarm-A/B/C



GRACE-FO C/D

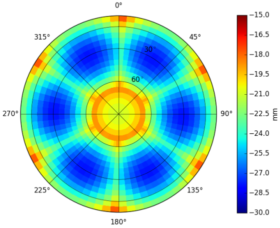


Jason-3

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

Methods

- 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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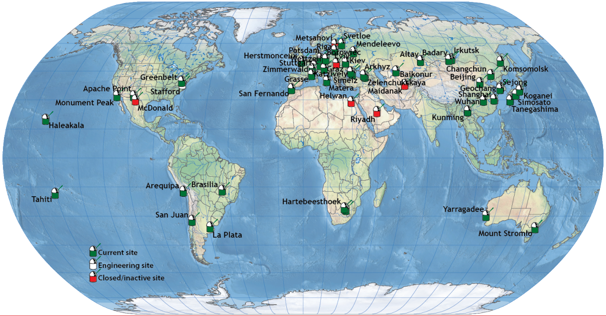
  - known station locations (SLRF2014/SLRF2020)



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  - state-of-the-art models (ILRS standards)

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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. parameters to estimate (e.g., station range or timing biases, coordinate corrections, ...)

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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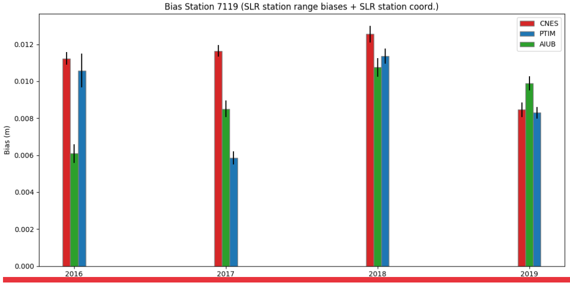
Copernicus POD QWG Bias Study

- In the frame of the Copernicus Precise Orbit Determination (POD) Quality Working Group (QWG): study to address SLR station biases and their determination from residual analysis to active LEOs
- AIUB, CNES/CS-SI, PosiTim (3 independent analysis software packages), DLR
- Estimation of yearly range biases for 2016-2019 using independent orbit sets



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

What about orbit errors?

Station errors

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

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- Incorrect CoM location
- Incorrect offset vectors (microwave sensors, laser reflector)
- deficiencies in force models
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Orbit offsets estimated for June 2021 based on 11 high-performing stations (no station parameters est.):

Satellite	dR [mm]	dT [mm]	dN [mm]
Jason-3	-0.1	12.9	0.5
Swarm-A	5.3	-2.3	-3.5
GFO-C	4.1	-7.0	-3.4
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

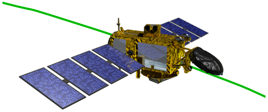
Sensitivity to orbit errors

Some station parameters for June 2021 (SLRF2014):

Estimated using original 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

(dE,dN,dU): Coordinate corr.
dr: Range bias
dt: Timing bias



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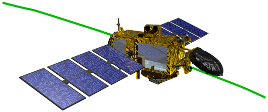
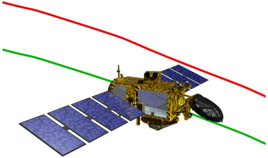


Estimated using orbits shifted by previous systematic errors

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



Correlations

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

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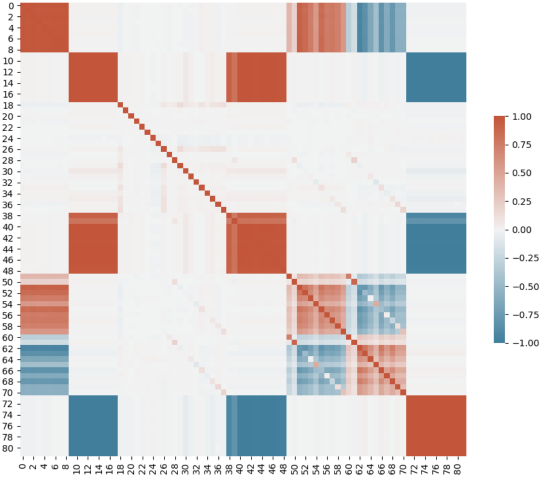

Estimated parameters (9 LEOs, 11 stations):

- 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).

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NNT constr.	-0.4	1.3	9.9	3.3	0.0

Local ties

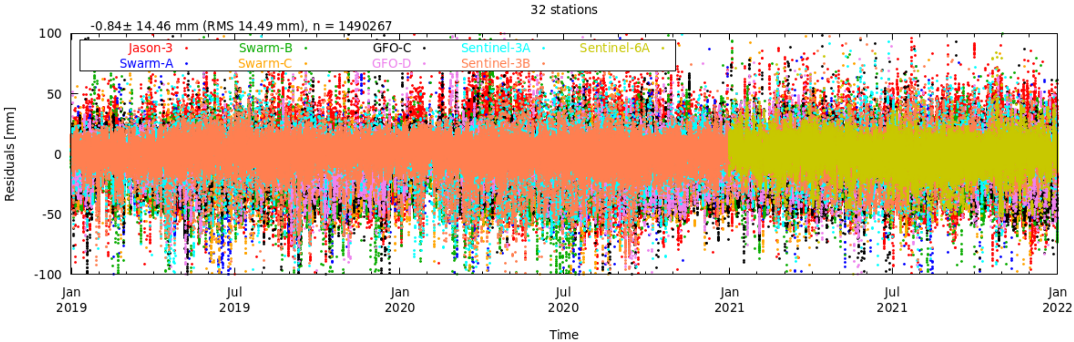
Coordinates of ZIM2 (GNSS) from ITRF2014
Coordinates of 7810 (Zimmerwald) from SLRF2014
Local tie ZIM2 $\leftrightarrow$ 7810

$\Rightarrow$ Need to shift 7810 by (-0.5/2.9/7.7) mm

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).

Residuals (1)

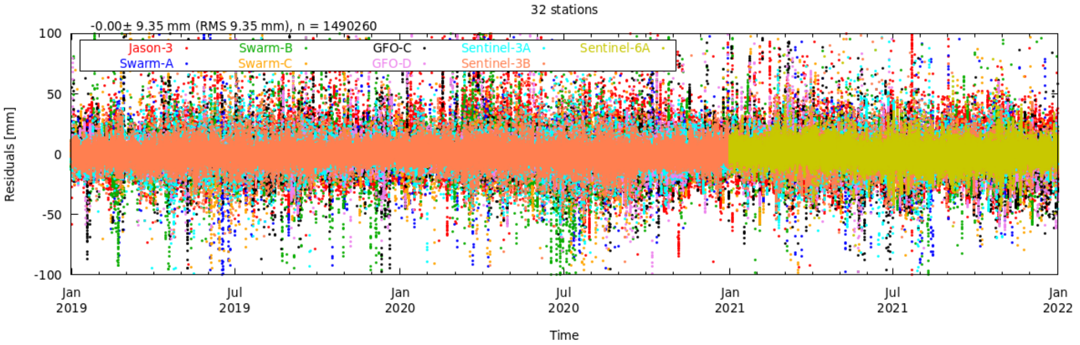
Residuals for 32 stations, 9 LEOs before ajustment:



RMS: 14.49 mm

Residuals (2)

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



RMS: 9.35 mm

Preliminary SLRF2020 results

- A priori coordinates from preliminary SLRF2020_POS+VEL_2022.04.29.snx
- Still using IGS14/IGb14-based LEO orbits
- Some station parameters for 2019 (SLRF2014/SLRF2020):

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Station	ID	dE [mm]	dN [mm]	dU [mm]
Riga	1884	-7.4/2.2	-7.3/3.9	207.9/10.6
Arkhyz	1886	22.5/11.4	-12.5/4.2	-169.9/-12.4
Svetloe	1888	5.8/4.0	7.8/5.2	-2.6/0.3
Badary	1890	6.9/2.9	2.5/-1.2	5.6/8.4
Katzively	1893	-2.5/2.0	-20.2/-5.8	-69.6/-12.9
Yarragadee	7090	4.8/0.4	-1.2/0.3	-2.0/-0.5
Greenbelt	7105	3.3/1.2	5.8/3.0	-12.4/-5.8
Haleakala	7119	4.9/2.9	-3.5/-1.8	1.9/4.0
Arequipa	7403	-0.3/5.3	2.2/0.6	11.5/-6.2
Hartebeesthoek (HRTL)	7503	-33.4/-0.9	-2.8/4.7	7.0/-1.7
Zimmerwald	7810	1.4/0.2	2.4/3.8	9.0/-0.4
Wettzell (SOSW)	7827	0.7/1.5	-8.7/4.2	-9.3/3.7
Simosato	7838	14.3/4.9	-10.0/-0.6	-56.6/-23.5
Graz	7839	3.1/0.9	3.3/4.3	0.0/-0.1
Herstmonceux	7840	3.3/0.0	1.8/3.6	-6.4/-1.0
Matera	7941	3.4/2.2	4.5/4.7	0.4/-1.9

- Significantly smaller coordinate corrections for majority of stations!

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Riga	1884	-7.4/2.2	-7.3/3.9	207.9/10.6	194.5/188.3
Arkhyz	1886	22.5/11.4	-12.5/4.2	-169.9/-12.4	-105.2/-104.8
Svetloe	1888	5.8/4.0	7.8/5.2	-2.6/0.3	-8.3/-8.0
Badary	1890	6.9/2.9	2.5/-1.2	5.6/8.4	12.6/12.6
Katzively	1893	-2.5/2.0	-20.2/-5.8	-69.6/-12.9	-47.1/-47.7
Yarragadee	7090	4.8/0.4	-1.2/0.3	-2.0/-0.5	2.5/2.5
Greenbelt	7105	3.3/1.2	5.8/3.0	-12.4/-5.8	-7.0/-7.0
Haleakala	7119	4.9/2.9	-3.5/-1.8	1.9/4.0	11.1/11.0
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Zimmerwald	7810	1.4/0.2	2.4/3.8	9.0/-0.4	8.9/8.9
Wettzell (SOSW)	7827	0.7/1.5	-8.7/4.2	-9.3/3.7	4.7/5.0
Simosato	7838	14.3/4.9	-10.0/-0.6	-56.6/-23.5	-72.9/-73.0
Graz	7839	3.1/0.9	3.3/4.3	0.0/-0.1	4.9/4.9
Herstmonceux	7840	3.3/0.0	1.8/3.6	-6.4/-1.0	-3.3/-3.3
Matera	7941	3.4/2.2	4.5/4.7	0.4/-1.9	-5.1/-5.3

- Significantly smaller coordinate corrections for majority of stations!
- Range biases very consistent

Preliminary SLRF2020 results (2)

- Also orbit offsets are consistent (zero-mean constraint for R offsets):

Satellite	dR [mm]	dT [mm]	dN [mm]
Jason-3	-0.2/0.0	10.2/10.3	0.3/0.1
Swarm-A	1.4/1.5	0.5/1.0	-3.8/-3.7
Swarm-B	-1.7/-1.8	0.0/0.4	0.6/0.9
Swarm-C	-0.1/-0.3	1.2/1.6	-4.7/-4.4
GFO-C	1.6/1.5	-1.7/-1.7	-1.2/-1.1
GFO-D	-0.7/-0.7	0.3/0.5	-0.8/-0.9
Sentinel-3A	0.3/0.3	0.1/0.3	0.4/0.3
Sentinel-3B	-0.6/-0.6	1.9/2.1	2.6/2.4

- SLR residuals before/after adjustment (29 stations):
  - SLRF2014: 0.6 ± 17.5 mm / 0.0 ± 8.3 mm $(n = 478'734)$
  - SLRF2020: 2.2 ± 22.8 mm / 0.0 ± 7.7 mm $(n = 487'030)$

Conclusions

- The numerous SLR observations to active LEOs have the potential to be used for the determination, monitoring and calibration of systematic station errors.
- Systematic orbit errors affect station parameter estimates and should be taken into account. When co-estimating them, constraints are needed for decorrelation.
- (Preliminary) SLRF2020 looks promising: Generally much smaller coordinate corrections, range bias and orbit offsets estimate consistent to SLRF2014-based results.

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Thank you for your attention!