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

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Motivation

- Numerous geodetic satellites are in low Earth orbit (LEO)
- Availability of GPS and SLR tracking
  - (Abundant) GPS tracking for precise orbit determination (POD)
  - (Sparse) SLR tracking for orbit validation
- What if GPS-based POD outperforms SLR in terms of accuracy?
  - Use GPS-based orbits as calibration standard for SLR
  - Monitor range (and timing) biases
  - Improve site coordinates and GPS/SLR frame tie
- Need
  - Good GPS-based POD solutions
  - Well surveyed LEO satellites (GPS antenna, center-of-mass, laser-retro-reflector)

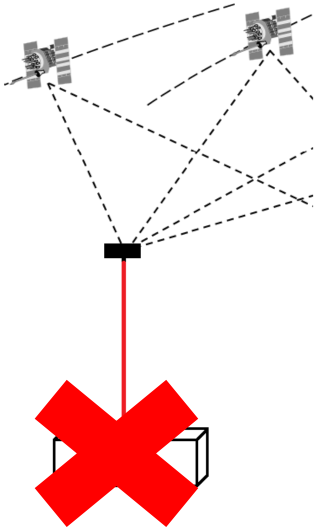
GPS-based POD of LEO Satellites

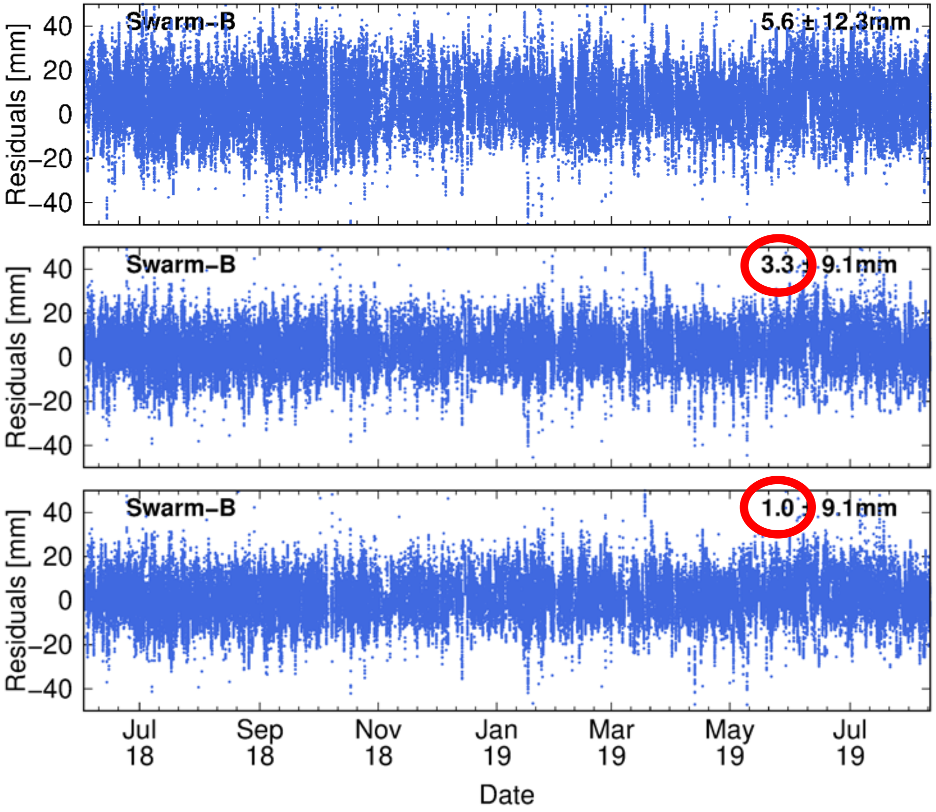
- Bernese GNSS Software
- State-of-the-art models
    - Macro models for non-gravitational forces
    - In-flight calibrated phase patterns
    - Spacecraft parameters (attitude, structure, CoM, sensor locations, etc.)
- Ambiguity fixing
    - Single-receiver ambiguity resolution using CODE’s GPS orbit and clocks together with CODE’s new signal-specific satellite phase bias product
    - Ties LEO orbit to IGSxx reference frame
    - Horizontal components benefit most, only weak constraint in vertical direction
- Missions: SWARM-A/B/C, Sentinel-1/2/3, GRACE-FO, …

Analysis of LEO SLR Data

- Compute SLR residuals based on
  - known LEO satellite orbit, attitude, geometry, LRA characteristics
  - known station location (SLRF)
  - state-of-the art models (IERS standards, 2-dim SLR range corrections)
- Compute partials of range measurements w.r.t.
  - satellite (in RTN frame) or LRA position (in s/c body frame)
  - station position (in ITRF or ENU frame)
  - SLR range and timing bias
- 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





Ambiguity−float, no non−grav. modeling

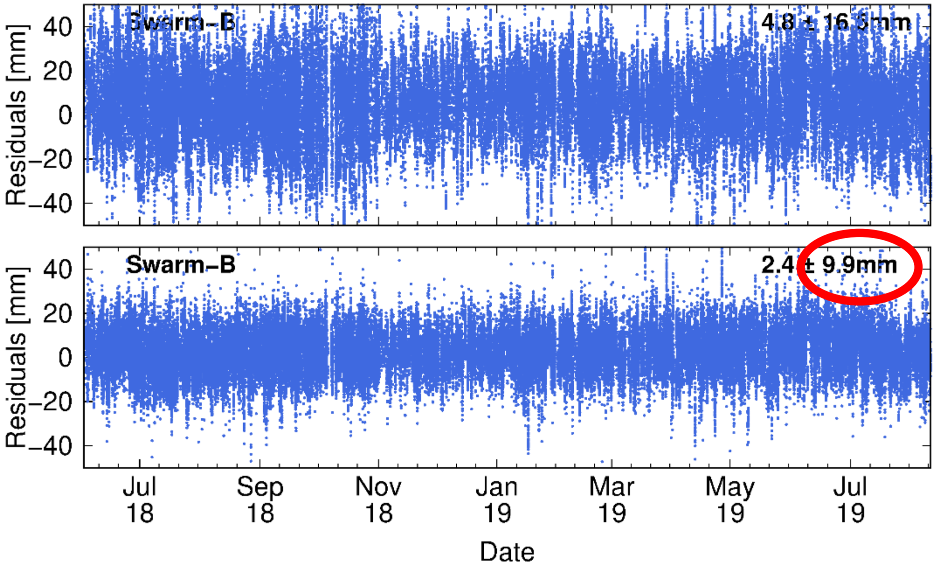
Ambiguity−fixed, no non−grav. modeling

Ambiguity−fixed, with non−grav. modeling

SLR observations of 14 high−performance SLR stations, 20 cm outlier threshold, 10° elevation cutoff. SLRF2014 station coordinates used. No parameters estimated.

SLR Residuals, Kinematic Swarm-B

Kinematic positions are purely geometrically derived from the GPS observations and fully independent on the force models used for LEO orbit determination.

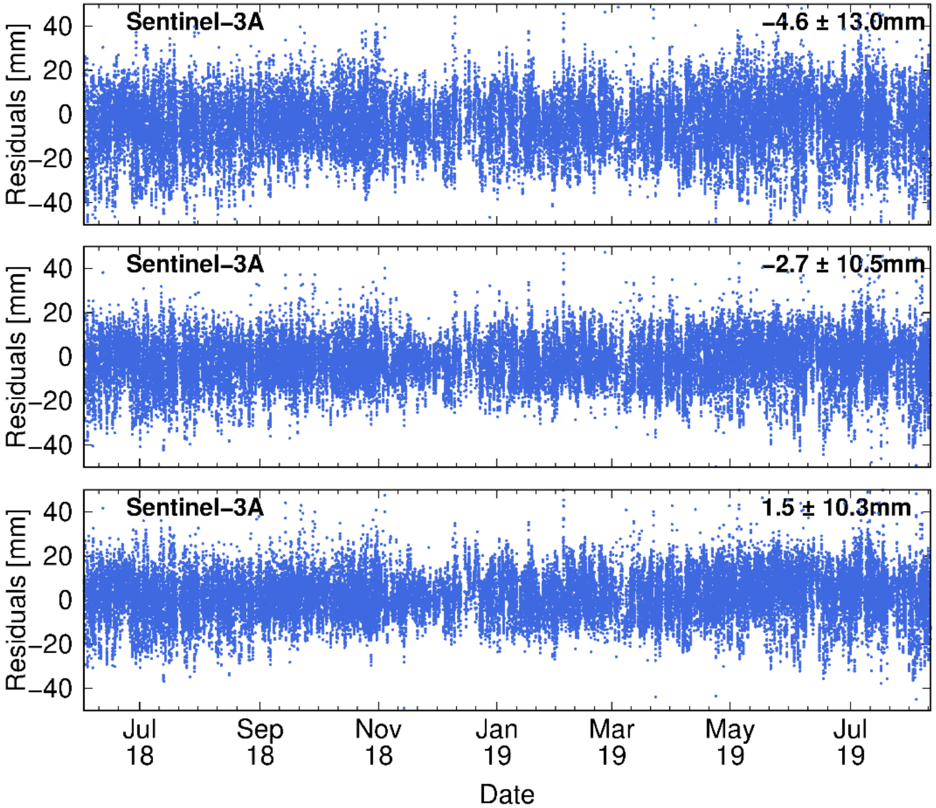


Ambiguity−float

Ambiguity−fixed

- The SLR STD of ambiguity−fixed kinematic orbits (9.9mm) is only marginally worse than for the ambiguity−fixed dynamic orbits (9.1mm, see previous slide).
- This nicely illustrates the limitation of SLR to "distinguish" between the orbits.
- Comparisons to ambiguity−fixed kinematic orbits should be regularly performed to detect inconsistencies, e.g., related to wrong GPS antenna phase center offsets.

SLR Residuals, Sentinel-3A



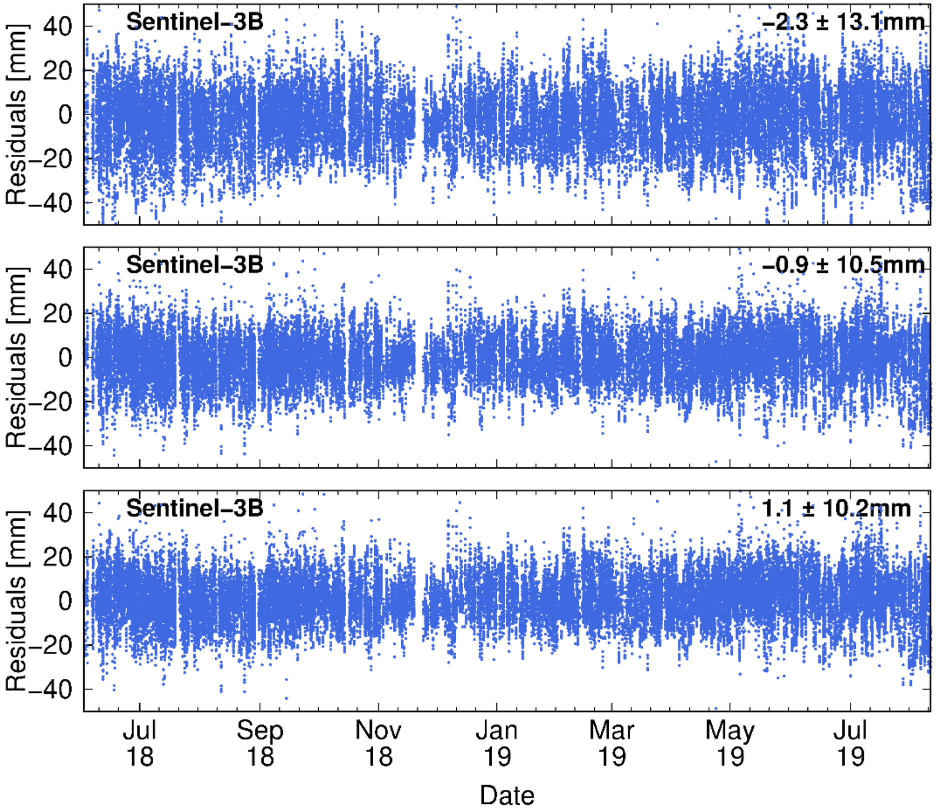
Ambiguity–float, no non–grav. modeling

Ambiguity–fixed, no non–grav. modeling

Ambiguity–fixed, with non–grav. modeling

Thanks to the refined strategy for the carrier phase generation out of low–level measurements proposed by Montenbruck et al. (2018), Sentinel POD is no longer harmed by half–cycle ambiguities and may therefore take full profit from single–receiver ambiguity fixing techniques.

SLR Residuals, Sentinel-3B



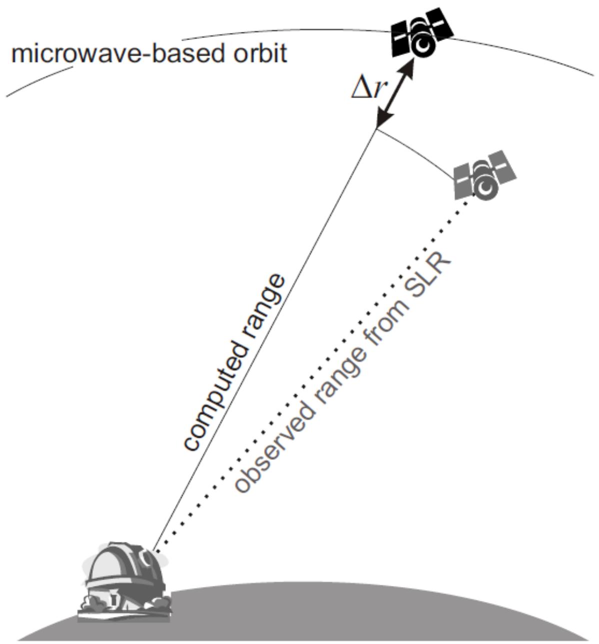
Ambiguity–float, no non–grav. modeling

Ambiguity–fixed, no non–grav. modeling

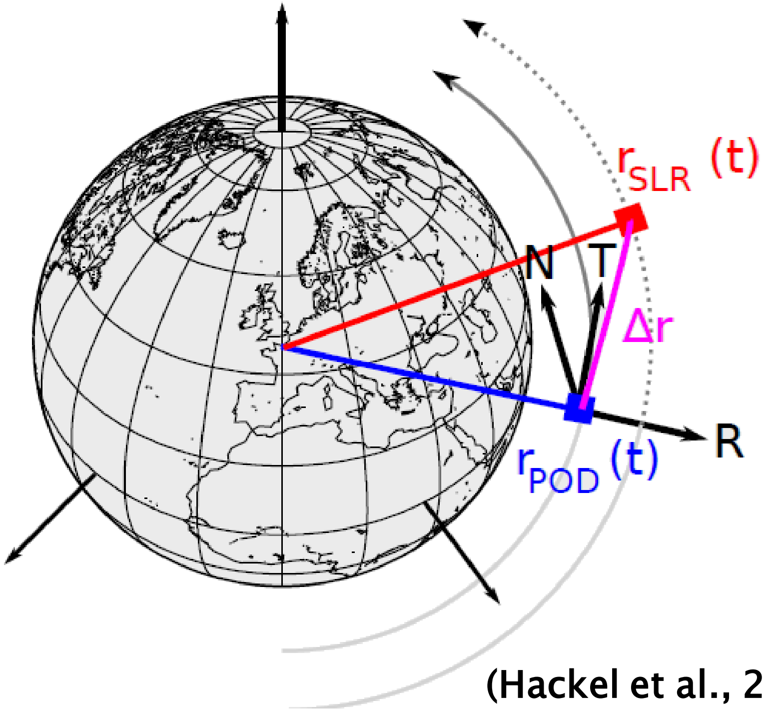
Ambiguity–fixed, with non–grav. modeling

SLR validation results are similar in terms of scatter for both Sentinel–3 satellites. Small differences of 0.4mm seem to be present in the resulting mean SLR biases.

SLR Validation Concepts



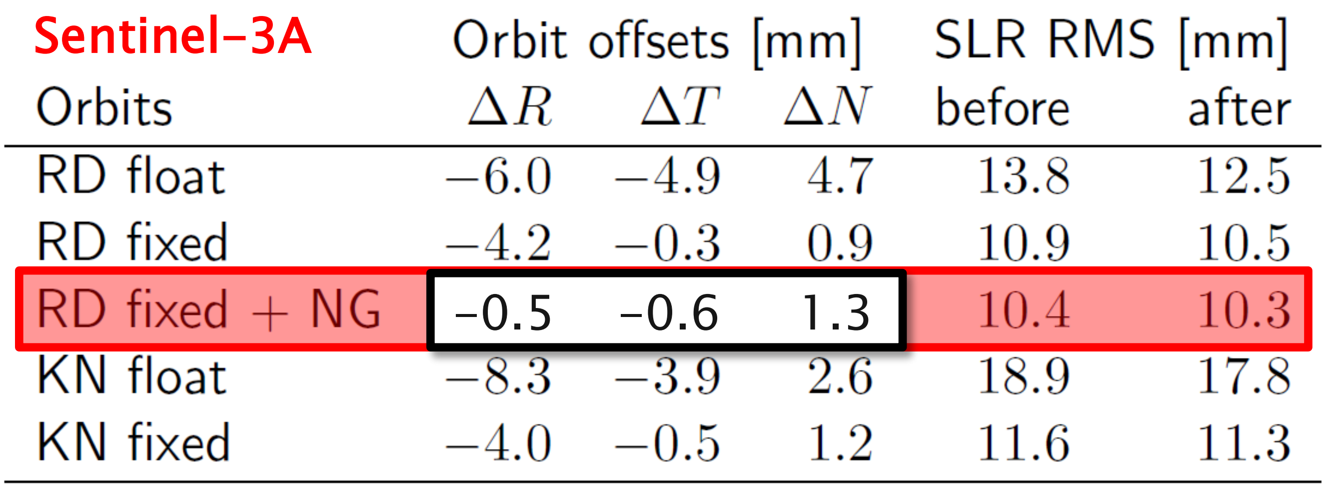
(Flohrer, 2008)



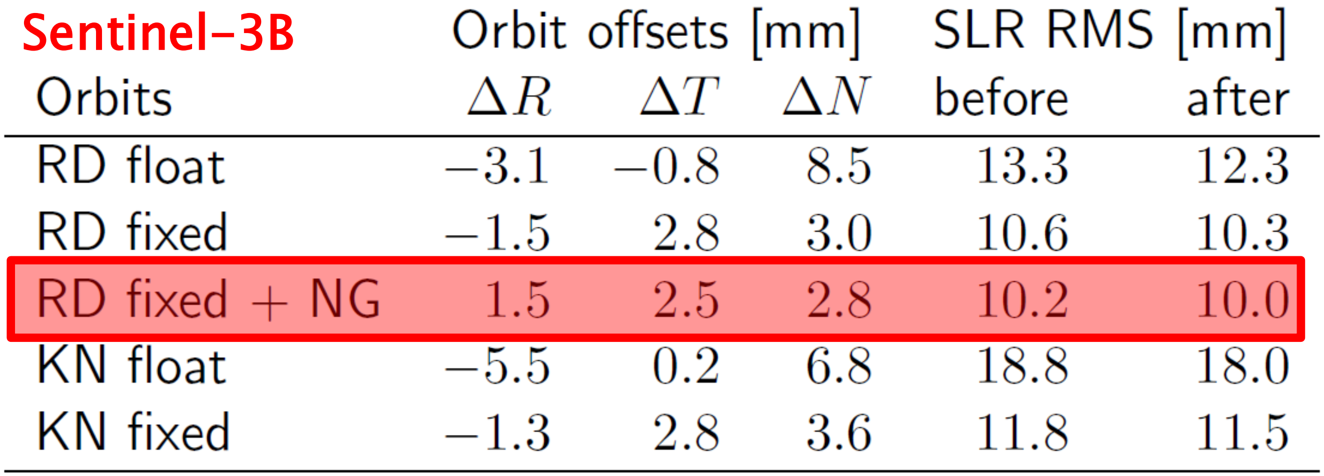
(Hackel et al., 2015)

Especially LEO satellites allow not only for a validation of the orbit quality in the radial direction, but also in the other directions. Using longer data spans, mean SLR biases may also be determined for the tangential (T) and normal (N) directions.

Sentinel-3A/B – SLR Offset Estimation



Sentinel–3A	Orbit offsets [mm]			SLR RMS [mm]	
Orbits	ΔR	ΔT	ΔN	before	after
RD float	−6.0	−4.9	4.7	13.8	12.5
RD fixed	−4.2	−0.3	0.9	10.9	10.5
RD fixed + NG	-0.5	-0.6	1.3	10.4	10.3
KN float	−8.3	−3.9	2.6	18.9	17.8
KN fixed	−4.0	−0.5	1.2	11.6	11.3



Sentinel–3B	Orbit offsets [mm]			SLR RMS [mm]	
Orbits	ΔR	ΔT	ΔN	before	after
RD float	−3.1	−0.8	8.5	13.3	12.3
RD fixed	−1.5	2.8	3.0	10.6	10.3
RD fixed + NG	1.5	2.5	2.8	10.2	10.0
KN float	−5.5	0.2	6.8	18.8	18.0
KN fixed	−1.3	2.8	3.6	11.8	11.5

~ 1mm discrepancy in the radial direction *ΔR*

Orbit Combination – an Additional Validation Tool

The framework of Variance Component Estimation (VCE) may be adopted to the individual orbit solutions from different processing centers to compute combined solutions by a simple weighted average from *n* individual input solutions. The following explicit formulas result:

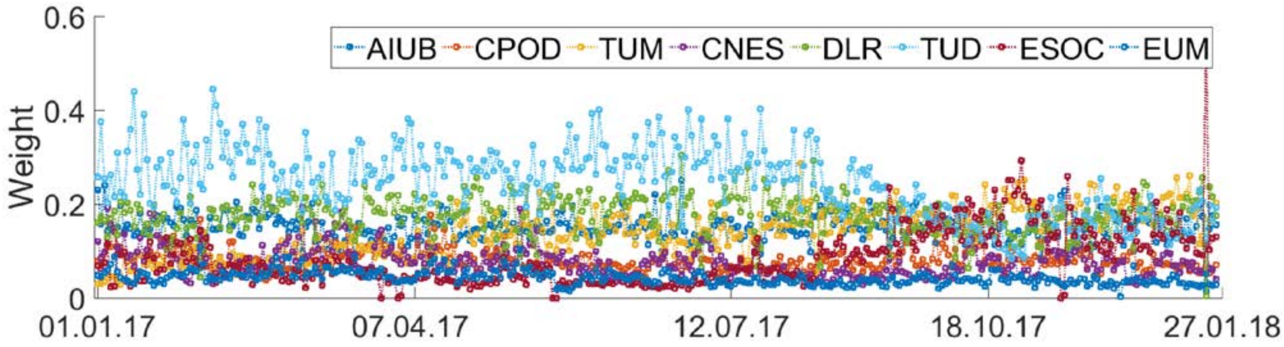
Iteration 0: $\hat{\mathbf{x}}_0 = \frac{1}{n}\sum_k \mathbf{x}_k$ with $w_{k,0} = \frac{1}{n} \quad \forall k,\ k = 1,\ldots,n$

Iteration $i > 0$: $\hat{\mathbf{x}}_i = \frac{1}{\sum_k w_{k,i}} \sum_k w_{k,i}\mathbf{x}_k$ with $w_{k,i} = (1 - \frac{w_{k,i-1}}{\sum_k w_{k,i-1}}) / \mathrm{RMS}(\mathbf{d}_{k,i-1})^2;$

$\mathbf{d}_{k,i-1} = \mathbf{x}_k - \hat{\mathbf{x}}_{i-1}$ Differences to the combined solution $\hat{\mathbf{x}}_{i-1}$ from the previous iteration

Note that iteration 0 is equivalent to a simple average, iteration 1 is equivalent to the simple weighted average. Further iterations are needed until the procedure converges. This method is subsequently adopted to the Sentinel-3A solutions of the Copernicus POD Quality Working Group.

Sentinel-3A – Orbit Combination Results



Weights compared to SLR validation: (Kobel et al., 2019)

AC	SLR STD (cm)	AC	Average Weight (%)
Combo	1.03		
TUD	1.10	TUD	24.6
AIUB	1.16	DLR	17.6
DLR	1.17	AIUB	15.0
CPOD	1.23	TUM	13.9
TUM	1.32	ESOC	8.5
ESOC	1.27	CPOD	8.3
CNES	1.38	CNES	7.7
EUM	1.69	EUM	4.4

Sentinel-3A – Orbit Combination Results

Results from Copernicus POD RSR #14, classical AIUB float solution:

AC	DLR	TUD	AIUB	ESOC	TUM	CPOD
Weight	28.7%	22.7%	16.2%	13.8%	13.0%	5.6%

Analogue analysis like for RSR #14, but classical AIUB fixed solution:

AC	DLR	TUD	AIUB	ESOC	TUM	CPOD
Weight	34.0%	17.3%	30.2%	6.8%	8.3%	0.3%

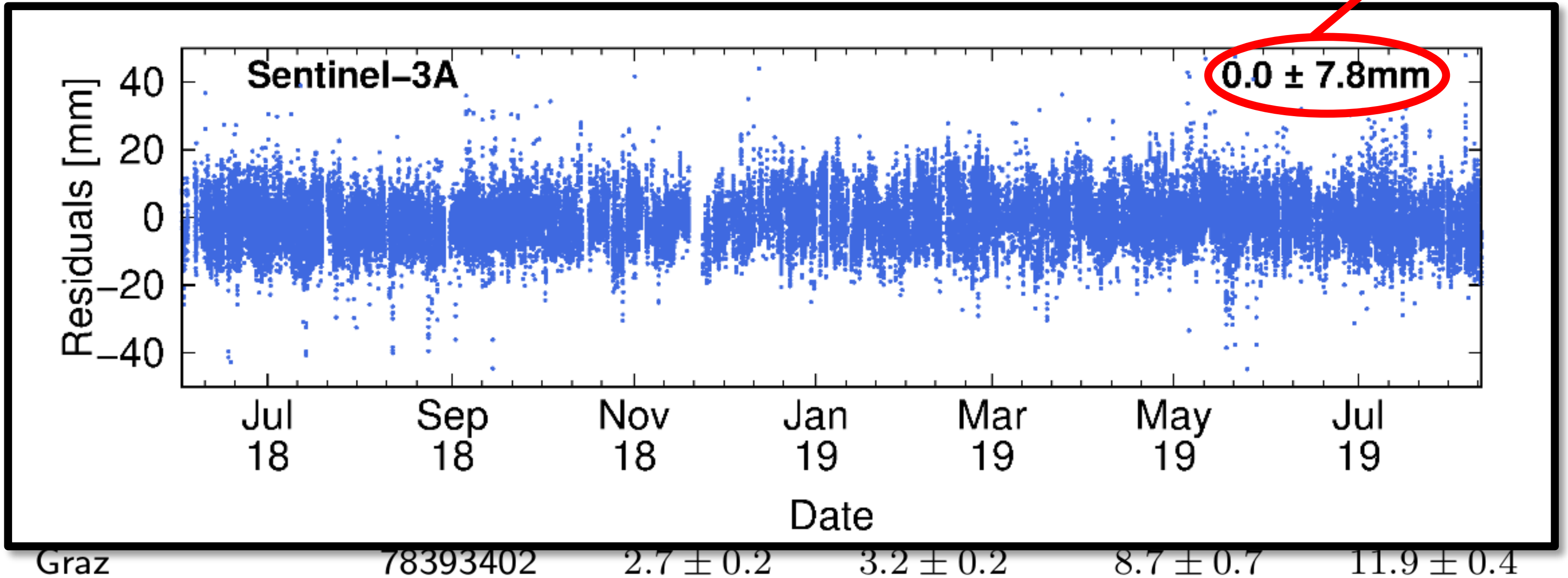
Analogue analysis like for RSR #14, but dynamic AIUB fixed solution:

AC	DLR	TUD	AIUB	ESOC	TUM	CPOD
Weight	34.9%	8.8%	41.4%	5.6%	6.8%	2.6%

The performance of the dynamic AIUB, ambiguity-fixed orbits is nicely reflected by the weights used for the combined solution.

Estimated Corrections wrt SLRF2014

Corrections from 1-year of dynamic, ambiguity-fixed Swarm-A/B/C, Sentintel-3A/B and GRACE-FO-C/D orbits.

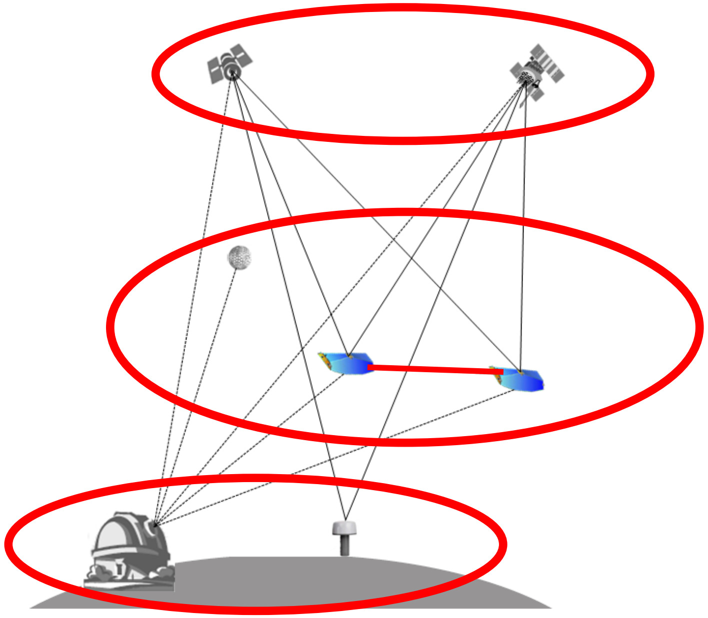


compared to 1.5 ± 10.5 mm

Graz	78393402	2.7 ± 0.2	3.2 ± 0.2	8.7 ± 0.7	11.9 ± 0.4
Herstmonceux	78403501	3.1 ± 0.3	1.5 ± 0.3	−4.1 ± 1.0	−2.5 ± 0.6
Potsdam	78418701	0.9 ± 0.3	3.7 ± 0.3	17.1 ± 0.9	−0.6 ± 0.6
Matera	79417701	1.7 ± 0.4	4.8 ± 0.4	4.2 ± 2.0	−5.3 ± 1.0

Some larger corrections ask for further investigations, e.g. comparisons to LAGEOS-based coordinate solutions. But that’s only the first step …

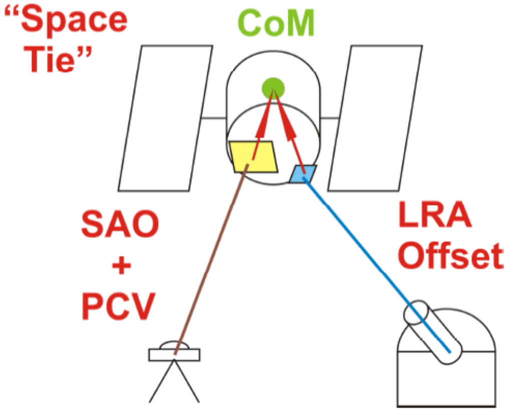
Outlook – ERC Project SPACE TIE



Data Basis

- ~ 80 GNSS satellites
- ~ 20 LEO satellites
  (**gravity** and **altimetry**)
- GNSS and SLR ground networks

=> A rigorous joint adjustment should be envisaged



Main Idea (in a nutshell)

- Use of the Earth's gravity field to act as an additional global tie via satellite orbits
- Exploitation of space co-locations (space ties) on both **GNSS** and **LEO** satellites

=> SPACE TIE has just started and will run for the next 5 years

Conclusion

- SLR is not only sensitive to radial orbit errors of LEO satellites, but also to errors in the tangential and normal directions.
- SLR LEO orbit validation results do not only reflect orbit quality, but also bad station coordinates, degraded SLR data, etc., etc.
- Dynamic ambiguity-fixed LEO orbits have reached a quality level that is interesting to validate the SLR station network.
- Kinematic orbits profit a lot from ambiguity-fixing. SLR sees now hardly any differences to the (superior) dynamic orbits.
- High-quality dynamic ambiguity-fixed LEO orbits are interesting for numerous applications in space geodesy.
- Further validation of the AIUB dynamic ambiguity-fixed orbits, e.g. in view of radial periodic errors as relevant for altimetry, should be performed in the near future.