Improving the SLR network calibration through GPS-based precise orbit determination of LEO satellites

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DLR Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

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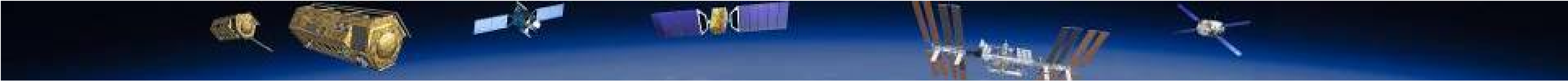
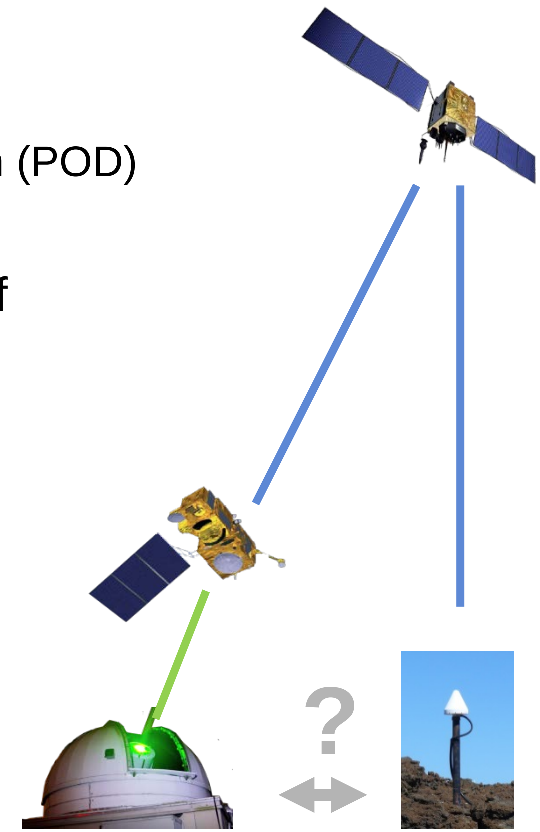


Improving the SLR network calibration through GPS-based precise orbit determination of LEO satellites

- Numerous geodetic satellites 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)

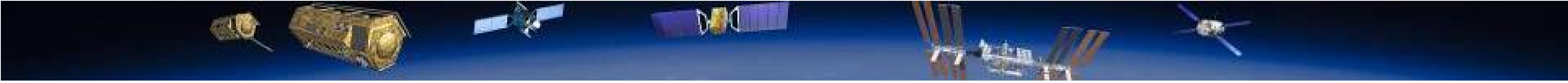


GPS-Based POD of Satellites in Low Earth Orbit

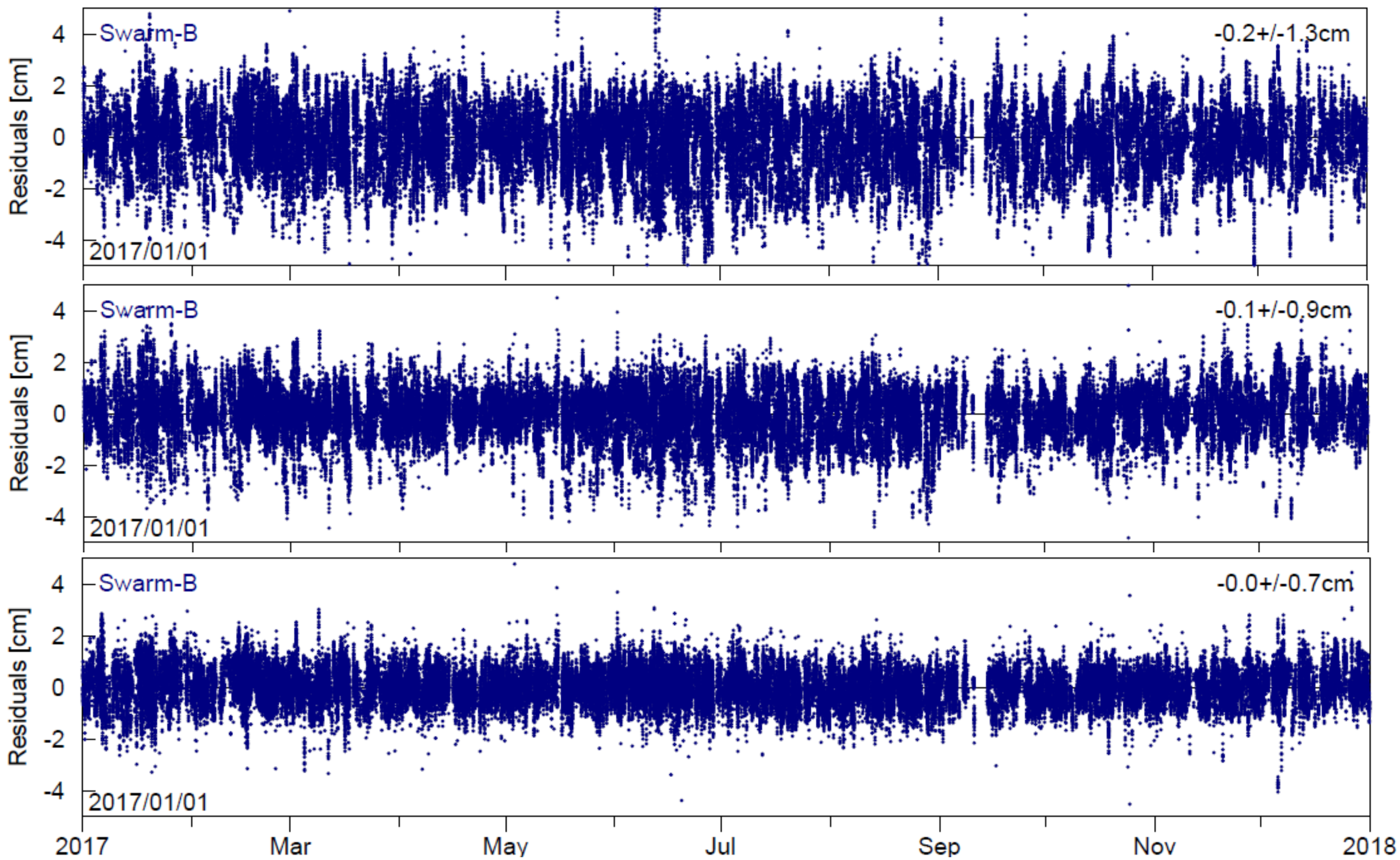
- DLR “GHOST” software
- State-of-the art models
  - Macro models for non-gravitational forces
  - In-flight calibrated phase patterns
  - Spacecraft parameters (attitude, structure, CoM, sensor locations, etc.)
- Ambiguity fixing
  - Single-receiver approach based on CNES/CLS products (orbit, clock, WL bias)
  - Ties LEO orbit to IGSxx reference frame
  - Horizontal components benefit most, only weak constraint in vertical direction
- Missions
  - SWARM-A/B/C (480/530km), TerraSAR-X (515km), Sentinel-3 (800km), Jason-2 (1300km)
  - Different altitudes and orbital planes
  - Period 2014-2017 (Swarm), 2016 (all others)

Approach

- 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 range corrections)
- Compute partials of modelled range w.r.t.
  - satellite position (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 2017, SLRF2014, 13 Stations



Float-ambiguity POD

1.3 cm

Ambiguity-fixed POD

0.9 cm

With SLR corrections

0.7 cm

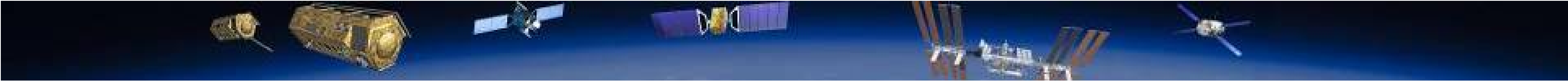
Estimated Corrections w.r.t. SLRF2014

Mean ± StdDev from four 1-year SWARM POD solutions for 2014, 2015, 2016, 2017

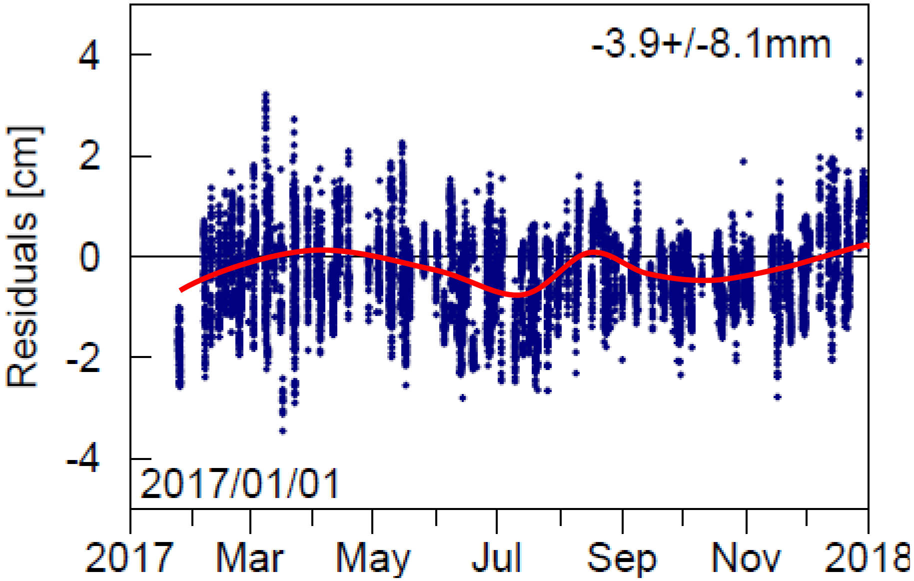
Station		SOD	East [mm]	North [mm]	Up [mm]	Bias [mm]
Arequipa	TLRS	74031306	1.5 ± 3.1	4.9 ± 3.1	15.1 ± 5.8	13.6 ± 1.9
Changchun	CHAL	72371901	-2.8 ± 1.0	0.4 ± 1.7	34.0 ± 2.9	6.2 ± 2.4
Graz	GRAZ	78393402	2.4 ± 1.2	-1.3 ± 1.0	9.0 ± 2.2	2.6 ± 2.4
Greenbelt	TLRS	71050725	7.1 ± 1.3	4.4 ± 1.0	-11.4 ± 2.1	-10.3 ± 2.6
Haleakala	TLRS	71191402	3.5 ± 3.1	3.1 ± 2.1	2.8 ± 5.7	9.3 ± 1.0
Hartebeest	MTLR	75010602	-2.6 ± 1.2	2.2 ± 2.2	-4.2 ± 3.5	-0.4 ± 3.9
Herstmonce	RGO	78403501	2.3 ± 0.6	-2.0 ± 1.4	1.6 ± 0.8	-3.1 ± 0.4
Monument P	MOBL	71100412	3.6 ± 3.2	-4.6 ± 3.1	-12.9 ± 3.6	-3.9 ± 1.9
Mount Stro	STR2	78259001	2.3 ± 1.0	1.1 ± 2.1	-0.3 ± 2.5	2.5 ± 2.3
Papeete	MOBL	71240802	6.0 ± 3.5	3.2 ± 1.4	-8.2 ± 2.4	-8.0 ± 2.2
Potsdam	GFZL	78418701	1.7 ± 1.2	-1.2 ± 1.5	15.4 ± 4.4	0.6 ± 3.0
Shanghai	SO F	78212801	-0.1 ± 2.5	0.0 ± 1.5	11.3 ± 2.9	-1.9 ± 11.0
Wettzell	SOSW	78272201	0.1 ± 1.9	-12.6 ± 2.4	-0.6 ± 6.8	7.0 ± 9.8
Wettzell	WLRS	88341001	0.6 ± 1.2	-2.8 ± 1.6	1.1 ± 5.0	-26.6 ± 1.7
Yarragadee	MOBL	70900513	1.3 ± 0.8	0.4 ± 2.6	-5.0 ± 2.6	0.8 ± 1.7
Zimmerwald	SWI2	78106801	1.6 ± 0.9	-2.1 ± 1.5	10.8 ± 1.2	1.1 ± 1.9

Discussion

- SLRF2014 provides notably better coordinates than SLRF2008 (even when compared with LEO orbits based on IGS08)
- Corrections at 1-cm level even for high-performance stations
- Scatter of four 1-year solutions indicates few mm uncertainties (exceeds formal uncertainties by 2x – 3x)
- Extreme cases
  - 18 cm up and bias correction for Riga (18844401) in 2016/2017
  - 9 µs time offset in Papeete (71240802) from ca. Oct. 2015 to June 2016
- Impact of corrections
  - Mean offset in SLR residuals for individual stations is removed
  - Reduced RMS and StdDev
  - Reduction depends on long-term range bias variations and length of data arc (more evident for annual solutions than for 4-year arc)



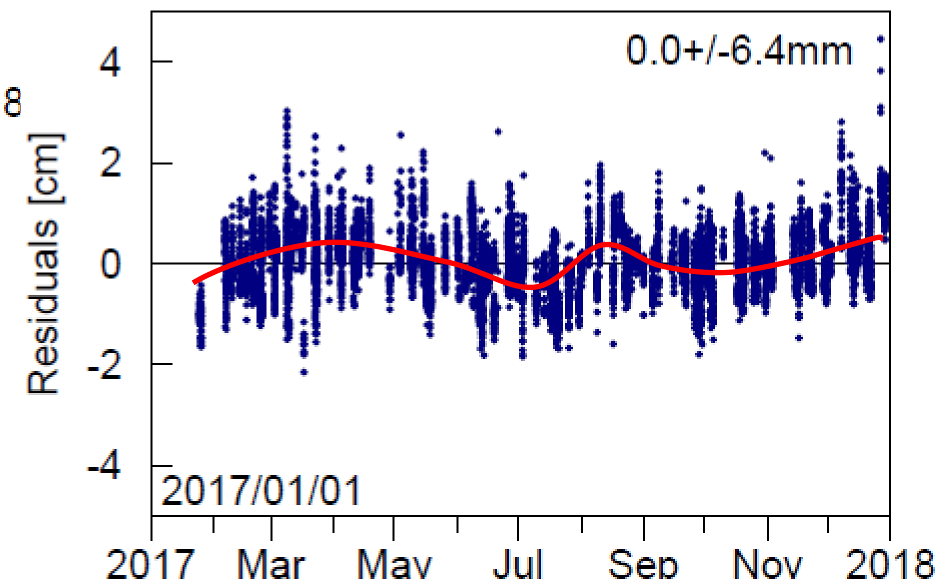
Example: Greenbelt TLRS-2 (71050725)



Swarm-B (2017)

Corrections	
East	+6 mm
North	+5 mm
Up	-8 mm
Bias	-7 mm

- Bias removed
- Global StdDev reduced
- Scatter within pass reduced



Conclusions

- SLR tracking of LEO satellites with GNSS receivers supports calibration of SLR stations and SLR/GNSS frame tie
- Turn SLR precision into SLR accuracy
- Differential correction based on SLR residuals for GNSS-only LEO POD
  - Lean processing
  - No need for joint use of GNSS/SLR in LEO POD
  - No need to store normal equations from GNSS-only LEO POD
- Use of "all" relevant LEO missions encouraged
  - Ambiguity fixed POD solutions strongly preferred
  - Needs good understanding of LEO satellites (antenna & reflector locations)
  - Needs careful screening of "bad" SLR measurements and orbit arcs

Methodology and further results are described in
Arnold D., Montenbruck O., Hackel S., Sosnica K.; *Satellite Laser Ranging to Low Earth Orbiters – Orbit and Network Validation*; Journal of Geodesy (2018) DOI10.1007/s00190-018-1140-4