Satellite Laser Ranging to Swarm satellites: validation, modeling of systematic effects, determination of global geodetic parameters, and realization of terrestrial reference frame

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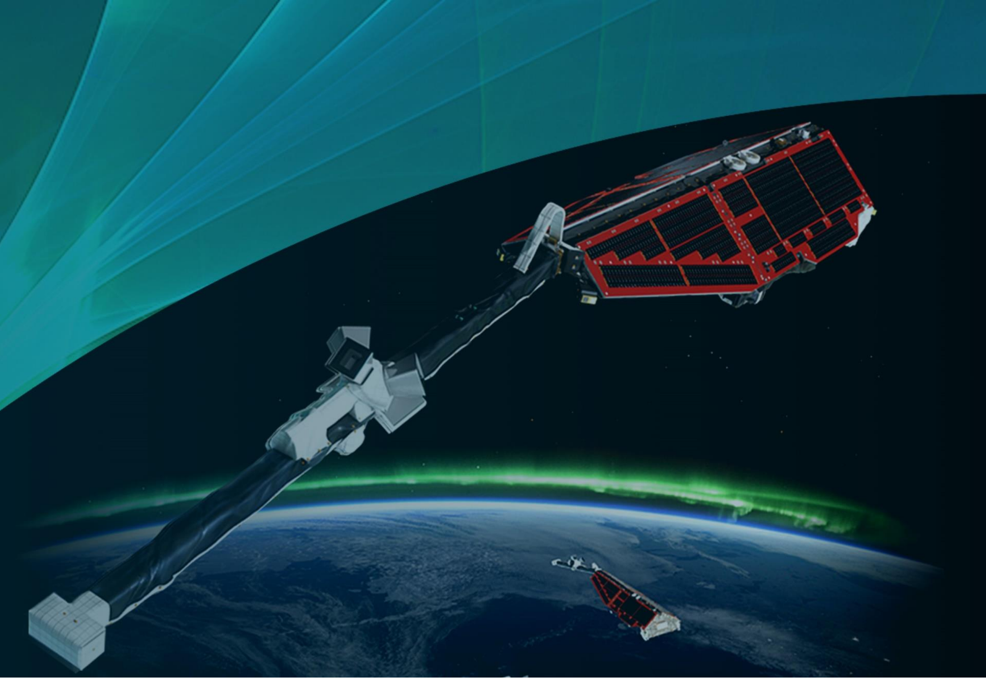

INTRODUCTION

Swarm satellites require precise orbit determination (POD) products to reach their mission goals, e.g., exploration of Earth's geomagnetic field and electric field in the upper atmosphere. Swarm spacecraft are equipped with Global Positioning System (GPS) receivers to provide the POD products and with laser retroreflectors (FIG. 1), which allow for satellite tracking using the Satellite Laser Ranging (SLR) technique. SLR measurements are provided by a global network of stations coordinated by the International Laser Ranging Service (ILRS). Many of them consider Swarm targets as the ILRS supports their tracking since the beginning of the mission (FIG. 2). Commonly, the SLR is used to validate POD products based on GNSS. We perform SLR-based validation of the POD products of Swarm satellites and show their quality assessment. We demonstrate that laser measurements to Swarm satellites can be successfully used not only for orbit validation, but also for modeling systematic effects affecting SLR measurements, such as range, tropospheric, or distance-dependent biases, as well as for determination of SLR station coordinates. Moreover, we investigate the possible deficiencies in the performance of SLR stations grouped by used detector type and the possibility for determination of global geodetic parameters provided by multi-satellite solutions, including Swarms (details in TAB. 1).

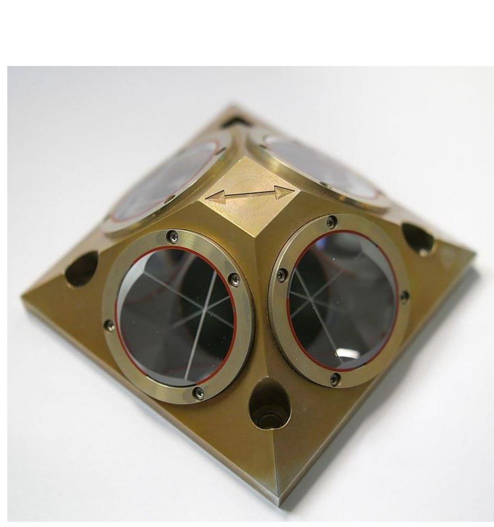

FIG. 1 Pyramidal SLR retroreflector mounted on Swarm satellites (earth.esa.int/eogateway/documents/20142/0/LRR-2.jpg)

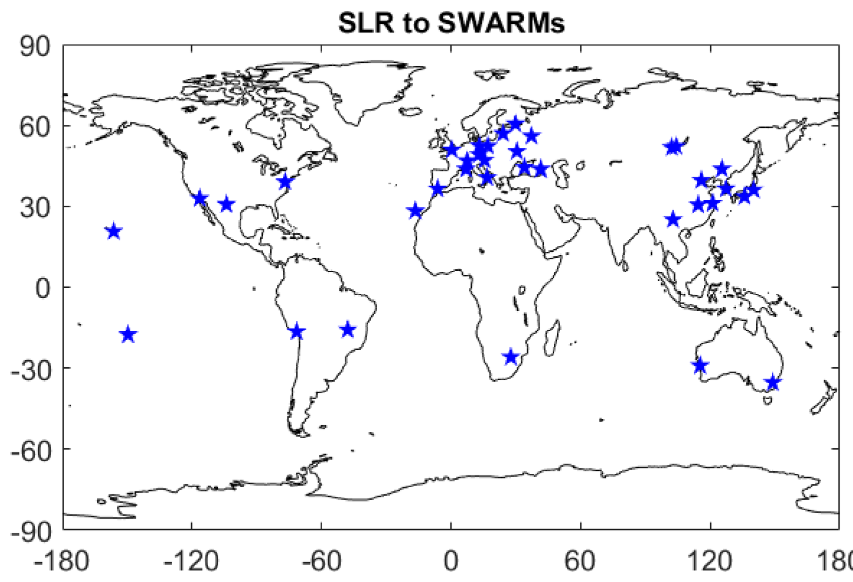

FIG. 2 The ILRS station network providing SLR observations to Swarm satellites

Satellites/ solution	SWA/B/C - Swarm-A, Swarm-B, Swarm-C LEO - eight low earth orbit satellites (Sentinel-3A, Grace-A/B, Jason-2, TerraSAR-X, Swarm-ABC), LAG-1/2 - Lageos-1/2 satellites, ALL - weighted multi-satellite solution (including LEO, LAG, LARES and GALILEO) SLR PPP – SLR Precise Point Positioning
ITRF/SLRF	ITRF2014 (SLRF2014) / ITRF2020 (SLRF2020)
Periods	2013.9-2024.0; 2018.5-2019.7; 2016.0-2017.0;
POD products	ESA - reduced-dynamic orbit, Astronomical Institute Uni. Of Bern (AIUB) - reduced-dynamic orbit
Station detectors test (# of stations)	Compensated Single-Photon Avalanche Diode (CSPAD - 8 stations) Micro-Channel Plate (MCP - 7 stations) Photo-Multiplier Tube (PMT - 7 stations)
Estimated parameters /corrections	Range bias (RB - daily), Troposphere bias (TB – daily) SLR station coordinates (weekly) geocenter, length-of-day excess, pole coordinates (weekly/daily)

TAB. 1 Processing details and solution description used in different tested solutions

SLR VALIDATION OF SWARM ORBITS

Figure 3 illustrates the SLR residuals of ESA orbits for a solution without modeling any systematic effects for Swarm satellites, over ten years of observations, and all stations. In general, validation results correspond with each other for Swarms and are at the mean(st.dev.) level of 0-2(~13) mm. However, the number of observations/day is about 2.8 times higher for B (~194) than for A (~72), and C (~70) Swarm satellites, which mostly orbit in a tandem configuration.
Figure 4 illustrates the mean and st.dev. of SLR residuals for station-satellite pairs. SLR network is inhomogeneous in terms of Swarms tracking quality. Some stations (e.g. most with id of 18xx, 7306, 7811, or 7824) are characterized with large offsets and discrepancies exceeding dozen of mm. Also, we can find ten high-performing stations, with mean(st.dev.) at the level of less than 5(10) mm, such as 7090, 7105, 7501, 7810, 7825, 7827, 7839, 7840, 7841, and 7941. These stations are also top contributors in the ILRS tracking, responsible for ~71% of all measurements to Swarm satellites.

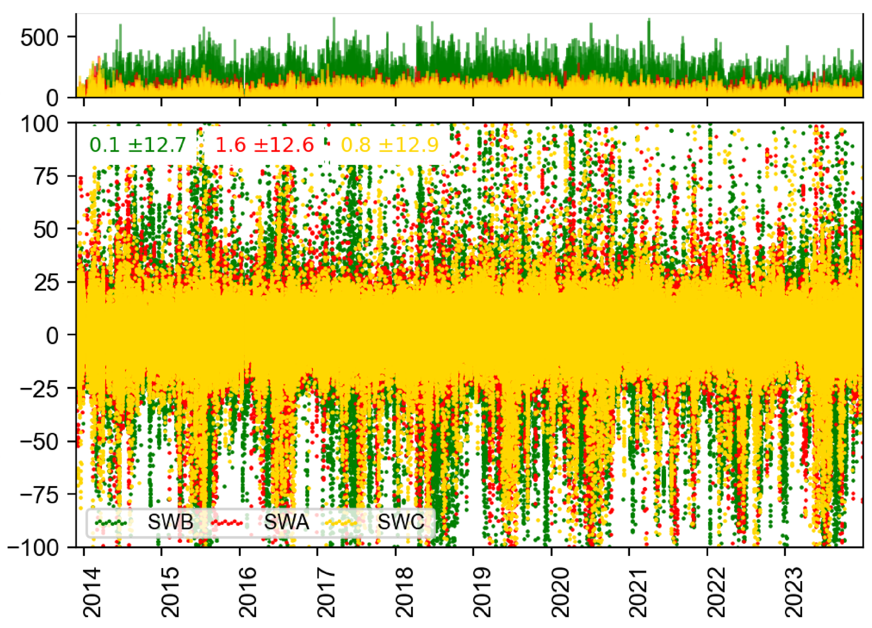

FIG. 3 Time series of SLR residuals to Swarm ESA POD products with mean+/-std. dev. (in mm) and number of observations/day (top)

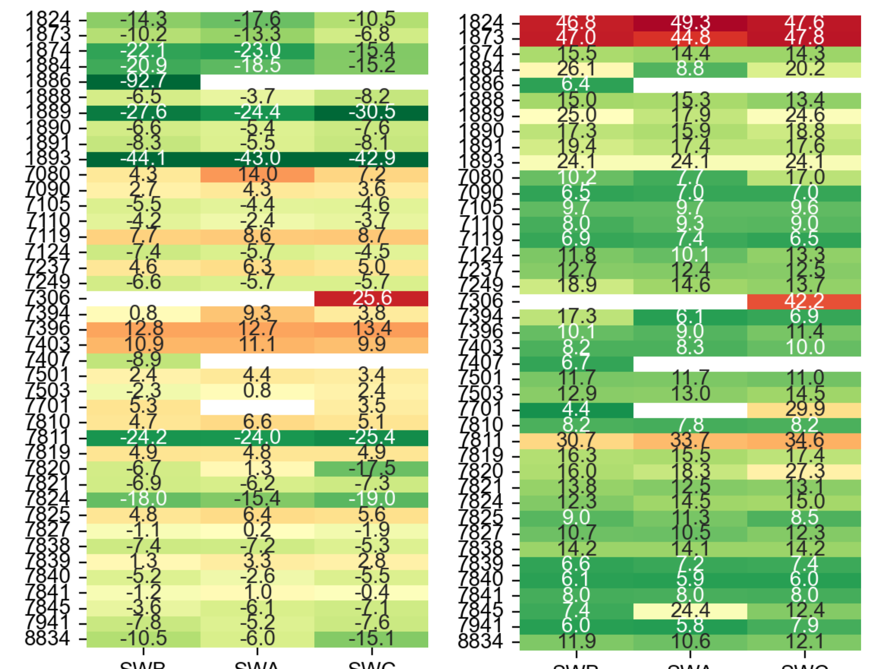

FIG. 4 Statistics of station-satellite SLR residuals for the period of 2013.9-2024.0 (mean – left, std. dev. – right, in mm)

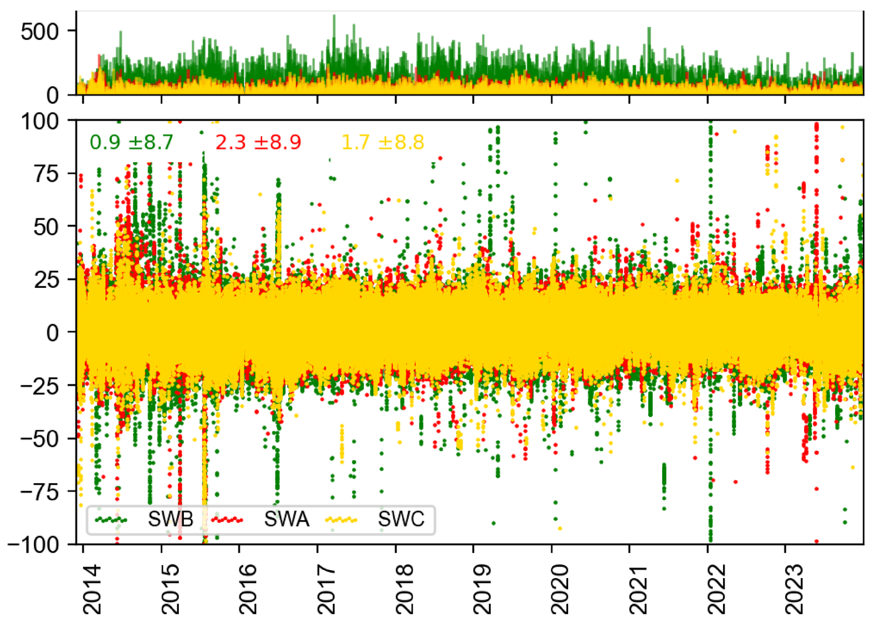

FIG. 5 Time series of SLR residuals to Swarm ESA POD products with mean+/-std. dev. (in mm) and number of observations/day (top) for high-performing stations

The residuals for ten high-performing stations (FIG. 5) show increased consistency between SLR measurements and ESA POD products with the st. dev. at the level of less than 9 mm for all Swarm satellites. However, the offsets of residuals are still visible at the level of 0.9, 2.3, 1.8 mm for Swarm B, A, and C, respectively.

MODELING OF SYSTEMATIC EFFECTS

Figure 6 top row illustrates SLR residual analysis without modeling systematic effects (RES) for two example SLR stations for Swarm-B, period 2018.5-2019.7. Residuals show a 10-mm offset and -0.16mm/° slope w.r.t. elevation angle. Analogical offsets are indicated in figures 4 and 5. Thus, we model the detected systematic effects using two types of corrections: a range bias (RB) which is a constant correction to station-satellite range, and a tropospheric bias (TB) which is a elevation-dependent correction.
Figure 7 illustrates the medians of daily estimated biases for selected stations and Swarm satellites. RBs and TBs are station-satellite dependent values, not stable in time. Corrections are within +/-15 and +/-8 mm range for the RBs and TBs, respectively, with consistent sign of values when considering a particular station or satellite. RBs reduce only the mean offset of residuals, whereas TBs reduce the offset of residuals, the dependency to elevation angle, and the spread of residuals (FIG.6 middle, bottom).
Figure 8 illustrates the histograms of SLR residuals for a solution with and without TBs for two different POD products: ESA and AIUB. Solutions with TBs are more consistent with different orbit solutions, where the % of residuals within +/-10mm has been increased from 56 and 68 to 70 and 91% for ESA and AIUB orbits, respectively. Moreover, solutions considering TBs reduce the st.dev. of residuals by 1 to 3 mm depending on station group and used orbit product.

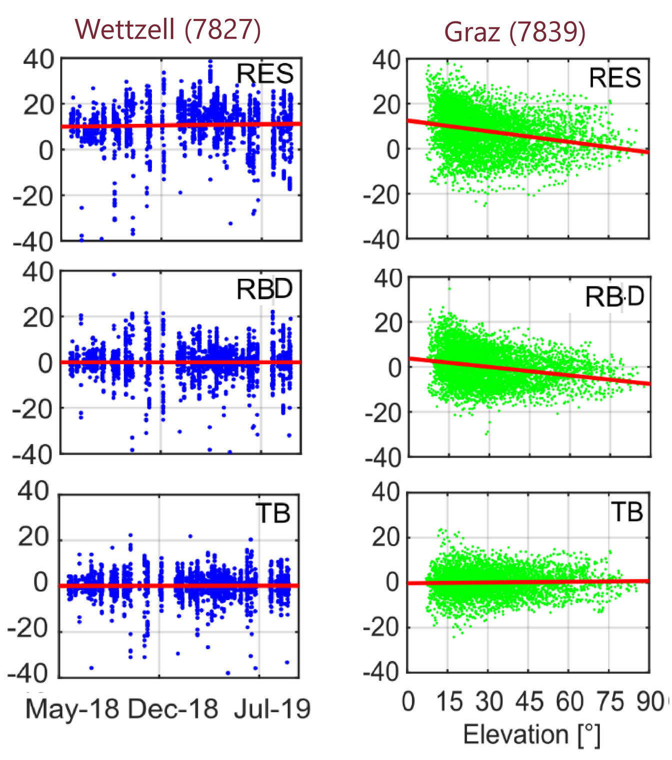

FIG. 6 SLR residuals to Swarm-B orbits w.r.t. time (left) and elevation angle (right) for selected stations without (top) and with RB (middle)/TB (bottom) corrections (in mm)

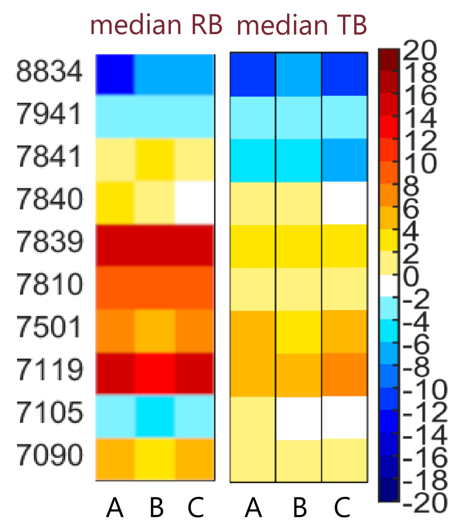

FIG. 7 Medians of estimated daily RB, TB corrections (in mm) for high-performing SLR stations and Swarm satellites

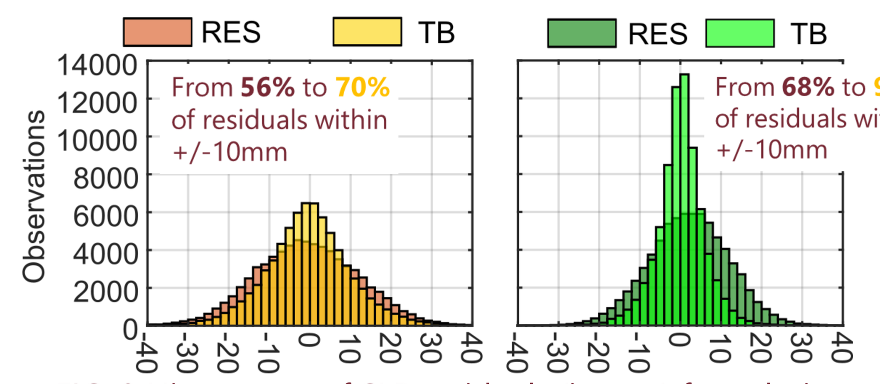

FIG. 8 Histograms of SLR residuals (in mm) for solutions without corrections (RES) and with TB correction for ESA (left) and AIUB (right) Swarm-B POD products

REFERENCE FRAME

Figure 9 illustrates repeatability (interquartile ranges, IQR) of estimated station coordinates based solely on SLR to Swarm data divided into groups considering satellite type and detectors on stations, i.e., multi-photon MCP, PMT, and single-photon CSPAD, for period of 2016.0-2017.0 (TAB.1). We test network constraining solution with no-net-rotation and translation constraints, and the so-called SLR-PPP solution with fixing the orbits and calculating the coordinates for each station independently (in analogy to GNSS-PPP). Station coordinates based solely on SLR data Swarm-ABC show the IQR for the Up, North, and East components at the level of 27, 15, and 17 mm, respectively for solutions with network constraining and similar results for the SLR-PPP solution. Solutions based on SLR only to Swarm-B are characterized with 1–5 mm worse IQRs than the Swarm-ABC solutions, whereas A and C solutions show a deteriorated station coordinate repeatability. The IQR of CSPAD station group is at the lowest level of 20 and 11 mm for the vertical and horizontal components, respectively. MCP stations exhibit poorer IQRs by a few mm, whereas PMT show worse IQRs by dozens of mm.

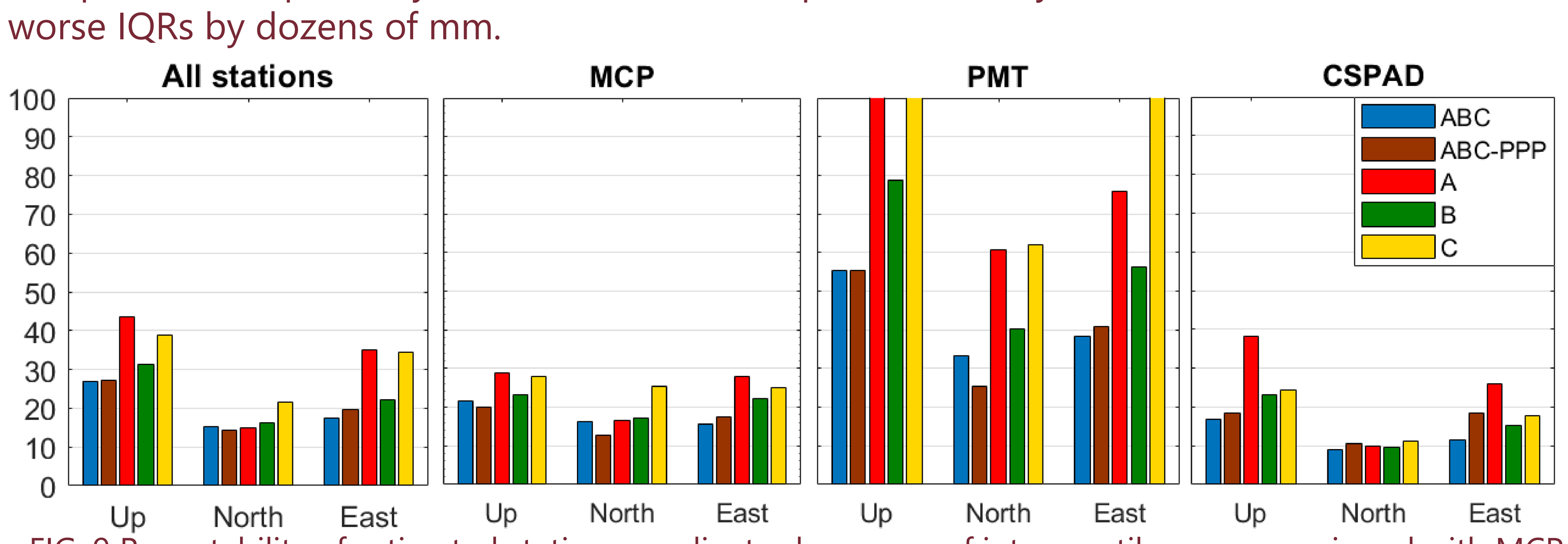

FIG. 9 Repeatability of estimated station coordinates by means of interquartile ranges equipped with MCP, PMT, and CSPAD detectors for different single-Swarm and combined Swarm-ABC solutions (in mm)

GLOBAL GEODETIC PARAMETERS

Figures 10, 11, and 12 show the pole coordinates, length-of-day excess, and the Z-geocenter coordinate, respectively, based on SLR solutions to LAGEOS-only satellites (LAG), low earth orbiters (LEO), and all tested satellites (ALL) for the period of 2016.0-2017.0 (TAB.1). SLR to Swarms successfully contributed to LEO and ALL solutions, whereas LAG is a reference solution used in standard SLR-processing.
For pole coordinates (FIG. 10), the LAG solutions show deviations w.r.t. IERS-C04-14 with root-mean-square (RMS) values of 0.191 and 0.175 mas for the X and Y components, respectively. LEO solutions are characterized by similar and slightly worse RMS of 0.191 and 0.209 mas for the X and Y pole coordinates, respectively. ALL solutions are characterized by the lowest RMS values of 0.155 and 0.167 mas for the X and Y pole coordinates, respectively. Length-of-day excess (FIG. 11) shows the best statistics for LEO and ALL with RMS values at the level of 0.053 and 0.049 ms/day, respectively. The mean values are close to zero. The LAG solutions show inferior statistics with the mean and RMS at the level of 0.015 and 0.169 ms/day, respectively. Z-geocenter coordinates show the general consistency between the solutions as well as the stability of the particular solutions. The RMS of the Z component is at the level of more than 5.4, 4.2, and 3.5 mm for the LAG, LEO and ALL solutions. The RMS of X and Y components are consistent within tested solutions at the level of 3 and 4 mm, respectively (not shown).

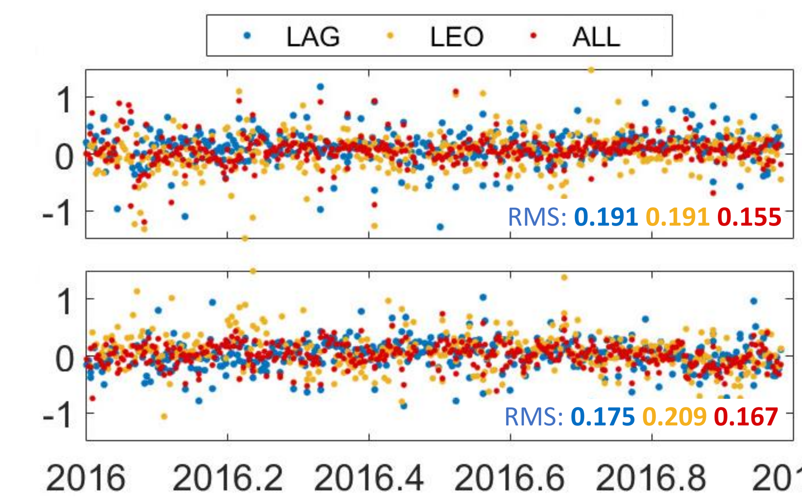

FIG. 10 Pole coordinates (X-top, Y-bottom, in mas) based on SLR to multi-satellite combinations w.r.t. IERS-14-C04

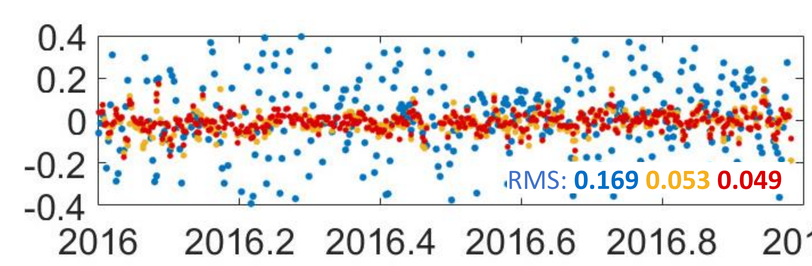

FIG. 11 Length-of-day excess (in ms/day) based on SLR to multi-satellite combinations w.r.t. IERS-14-C04

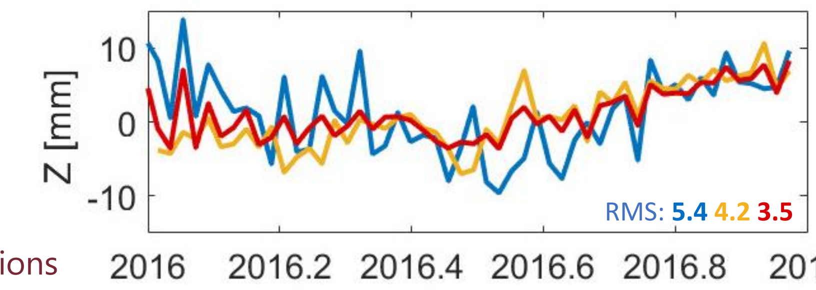

FIG. 12 Z-geocenter coordinate (in mm) based on SLR to multi-satellite combinations

CONCLUSIONS

New applications of Swarm mission data! SLR observations to Swarm satellites:

- allow us to validate the GPS-based POD products: 10-year ESA POD products are consistent with SLR at the level of ~9(~13) mm for high-performing(all) stations
- can be used for detection of systematic effects in SLR: some stations are characterized with offsets and slopes of SLR residuals, stations with PMT detectors show inferior quality of data
- can be used for modeling systematic effects in SLR: troposphere biases better absorb errors than range biases as they reduce offsets, slopes, and the spread of residuals – consistency between ESA POD products is further improved by ~3 mm
- enables determination of the SLR station coordinates: in network constraining and SLR-PPP mode (~20 mm repeatability of coordinates)
- enables determination global geodetic parameters (geocenter, pole coordinates, and length-of-day) as a part of multi-satellite solution

References

Strugarek D., et al. (2021) Determination of SLR station coordinates based on LEO, LARES, LAGEOS, and Galileo satellites, Earth P. & S., Vol. 73 No. 87. DOI: 10.1186/s40623-021-01397-1
Strugarek D., et al. (2021) Detector-specific issues in Satellite Laser Ranging to Swarm-A/B/C satellites, Measurement, Vol. 182 No. 109786 DOI: 10.1016/j.measurement.2021.109786
Strugarek D., et al. (2022) Satellite laser ranging to GNSS-based Swarm orbits with handling of systematic errors GPS Solutions, Vol. 26 No. 104, DOI: 10.1007/s10291-022-01289-1
Strugarek, D. (2022). Satellite Laser Ranging to Low Earth Orbiters for Orbit Validation and Determination of Global Geodetic Parameters. PhD Dissertation. Wrocław: Krzysztof J. Sośnica.

* Moreover, SLR to Swarms greatly allowed me to obtain my PhD degree at UPWr!

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