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 Lidar for geocenter determination (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 these swarm targets are the ILRS supports the determination of the mission (Fig. 2). Commonly, the ILRS is used to validate POD products based on GNSS. We present ILRS-based validation of the POD products of the Swarm satellites for the purpose of 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 the POD results, e.g., troposphere effects, as well as determination of SLR station coordinates. Moreover, we investigate the possible deficiencies in the performance of SLR stations grouped by user detector type and the possibility for determination of global geodetic parameters provided by multi-station solutions, including Swarm stations (details in Tab. 1).

SLR VALIDATION OF SWARM ORBITS
Figure 3 illustrates the SLR residuals of ESA orbit solutions for Swarm satellites, over ten years of observations, and all satellites. In general, validation results correspond with each other for Swarm and SLR satellites, and are at the median(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 std.dev. of SLR residuals for single-satellite pairs. SLR network is inhomogeneous in terms of Swarm tracks, i.e., quality. Some stations (e.g., mobilenews with lidar, 1784, 784, 784) are characterized with large residuals and large standard deviations associated with them. Also, we can find ten high-performing stations, with median(std.dev.) at the level of less than 5(10) mm, such as 7090, 7105, 7075, 7840, 7834, 7841, 7881, and 7891 are characterized with large residuals and large standard deviations associated with them. These stations are also top contributors in the ILRS tracking, responsible for <7% of all measurements to Swarm satellites.

MODELING OF SYSTEMATIC EFFECTS
Figure 5 illustrates SLR residuals analysis without modeling systematic effects (RES) for two example SLR stations for Swarm-B, period 2015.8–2017.9. Residuals show a 10-mm offset and 0.16∗mm/day slope w.r.t. elevation angle. Anomalies indicated are offsets in Figures 4 and 5. Thus, we observe the detection of systematic effects using the 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-dependent values, not stable in time. Corrections are applied to Swarm-A solutions for ESA and AUB solutions for TB. RBs only reduce the mean offset of residuals, whereas TBs reduce the offset dependence to elevation angle, and the spread of residuals (RESmedian bottom).

REFERENCE FRAME
Figure 8 illustrates the histograms of SLR residuals for a solution with and without TBs for two different stations: ESA and AUB. Solutions with TBs are more consistent with different orbit solutions, where the % of residuals within ±/70 mm has been increased from 56 and 68 to 70 and 91% for ESA and AUB orbits, respectively. Moreover, solutions considering TBs reduce the stdev of residuals by 1.5 to 3 mm depending on station group and used orbit product.

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 LAGOS-only satellites (LAG), low earth orbiters (LEO), and Swarm satellites (56) for the period of 2015.0–2017.0 (Tab. 2). SLR to Swarm satellites 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 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 0.115 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 of 0.054 and 0.049 mas/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 mas/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).

CONCLUSIONS
New applications of Swarm mission data: SLR observations to Swarm satellites:
• All solutions are consistent with the GPS-based POD products: 10-year ESA POD products are consistent with SLR at the level of ~9–13 mm for harmonic orbit error.
• can be used for detection of systematic effects in SLR: some stations are characterized with offsets and slopes of SLR residuals, stations with few observations.
• can be used for modeling systematic effects in SLR: troposphere biases better absorb errors than range biases as they reduce offsets, and the spread of residuals – consistency between ESA POD products is further improved by ~3 mm.
• New solutions can be used for determination of global geodetic parameters (geocenter, pole coordinates, and length-of-day) as a part of multi-satellite solution.

References

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