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Modeling of systematic effects in SLR observations to Swarm satellites for determination of global geodetic parameters

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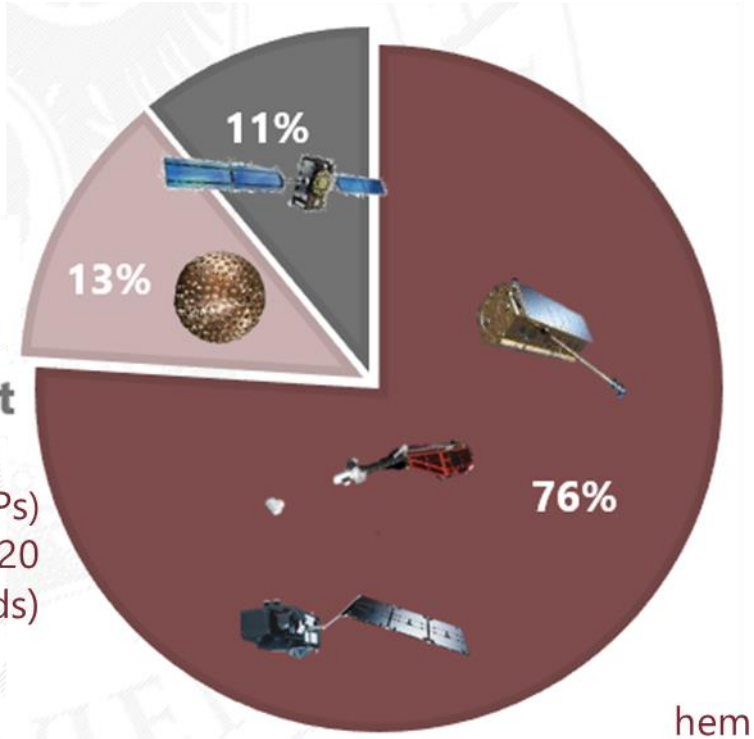
Motivation - SLR to LEOs



% of SLR observations (NPs) to particular satellite types in 2014-2020 (ILRS quarterly report cards)

SLR retroreflectors onboard LEOs: pyramidal, spherical, hemispherical shapes, (source: IPIE/ESA/EUMETSAT/DLR/GFZ)

Since recent decade we observe a **rapid emergence of active low Earth orbit satellites** (LEOs) in space.

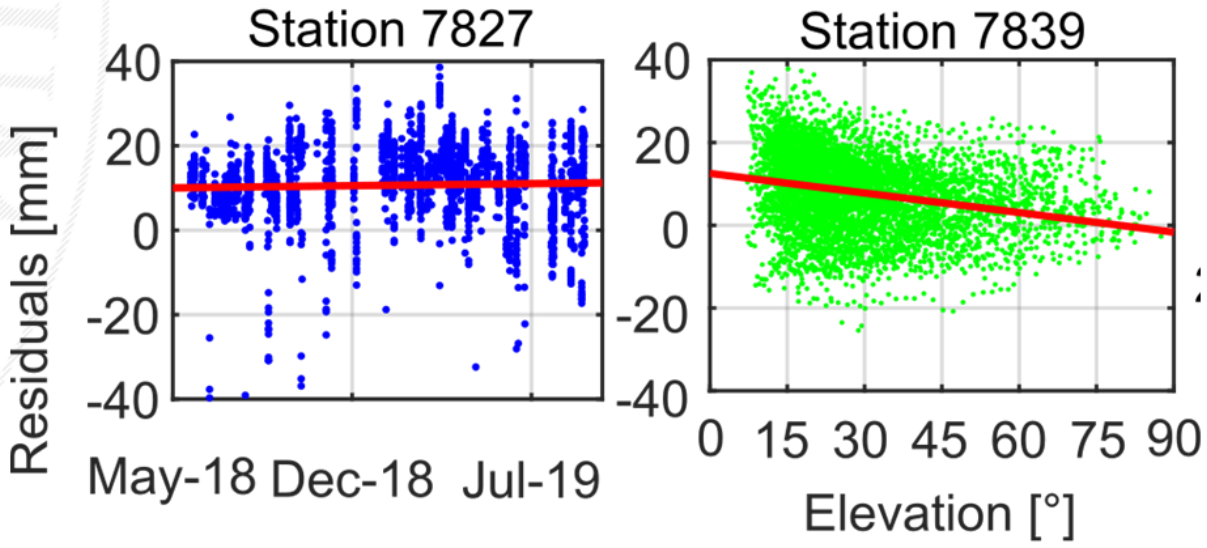
Many of them are equipped with **GNSS** receivers for precise orbit determination (POD) and Satellite Laser Ranging (**SLR**) **retroreflectors** for orbit validation.

SLR measurements to LEOs provided by globally distributed network of stations constitute **76% of all observations** (remaining are spherical geodetic and GNSS satellites).

Motivation - high quality of LEO POD products

- **GNSS/DORIS/SLR technique combinations for LEO POD**
- **Improvements of the GNSS/DORIS/SLR techniques performance and products**
- **Developments of LEO POD strategies and procedures**

The current consistency of microwave based POD products of LEOs with SLR observations is at the level of 1-cm or better, e.g.: **11 mm** for Sentinel-3A/B (Berzosa-Molina et al. 2021), **8 mm** for SWARM-C (Mao et al. 2021), **9.4 mm** for multi-LEOs (Arnold et al. 2019, 2022), **9.7 mm** for Sentinel-6A (Montenbruck et al. 2021)



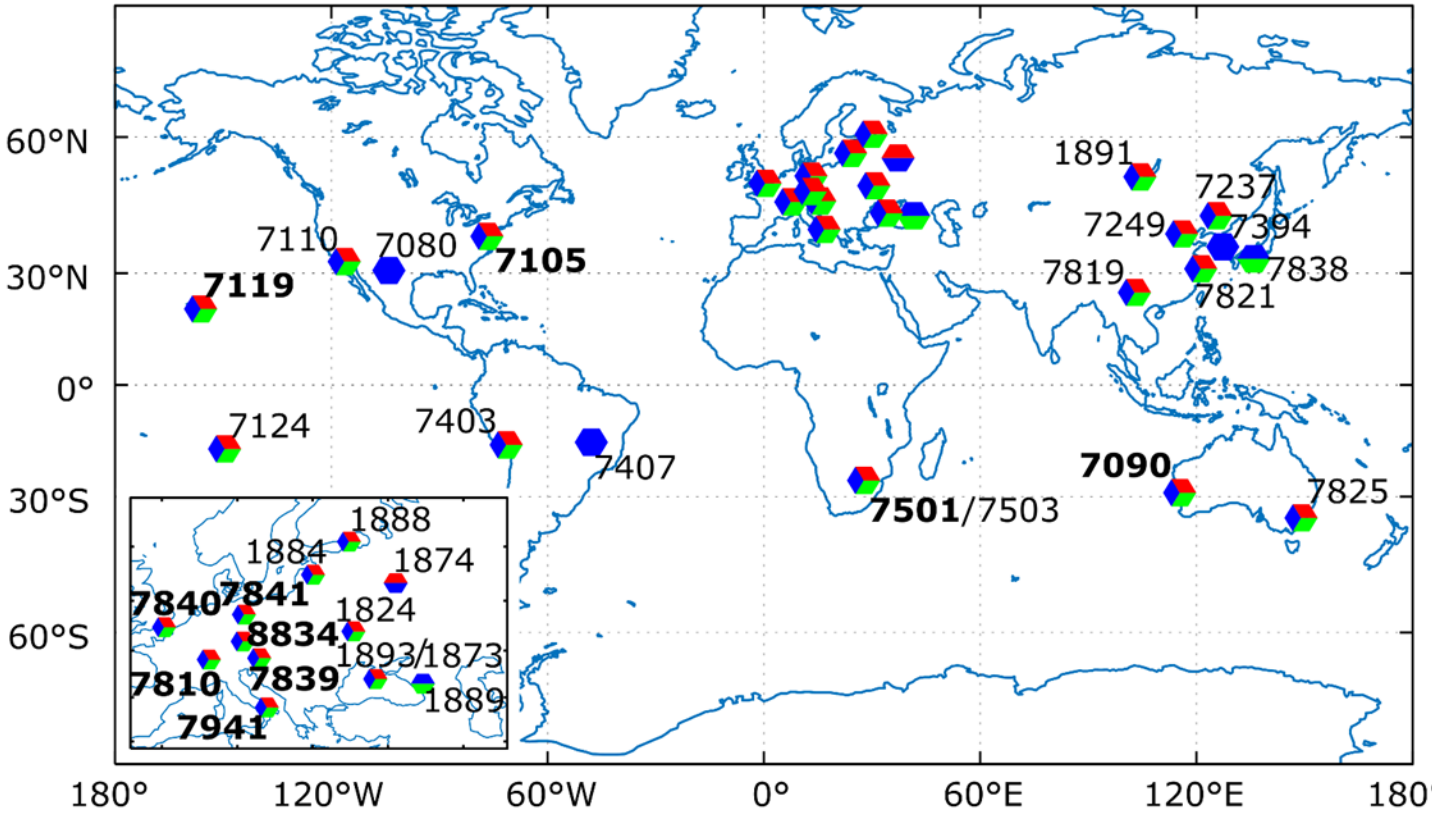
Systematic effects in SLR residuals for Swarm-B from Wettzell (7827), Graz (7839) from June 2018 to August 2019

We investigate…

improving the consistency between SLR observations and microwave POD products of LEOs, i.e,. SWARM-ABC satellites

determination of SLR station coordinates and global geodetic parameters based on SLR measurements to LEO SWARM-ABC satellites and multi-satellite combinations

all with introducing modeling of systematic effects in SLR – range biases, troposperic delay correction



- SLR measurements for the period 2018.42–2019.67 (~1.3 year), 32 SLR stations, ~40 000 obs. for A, ~39 000 obs. for C, ~112 000 obs. for B, total ~191 000 obs. (normal points from CDDIS/EDC)
- Comparison with SLRF2014, LAGEOS-only solution

Swarm-A (red), Swarm-B (blue), Swarm-C (green)

SLR processing scenarios

Estimated parameters / Solution	Range bias	Troposphere delay correction/bias
RES		
RB	X	
TRP		X

1-day → SLR-based validation of different a priori GPS orbit solutions:
reduced-dynamic (AIUB, Mao et al. 2020)
reduced-dynamic (ESA, van den IJssel et al. 2015) kinematic (AIUB, Jäggi et al. 2016)

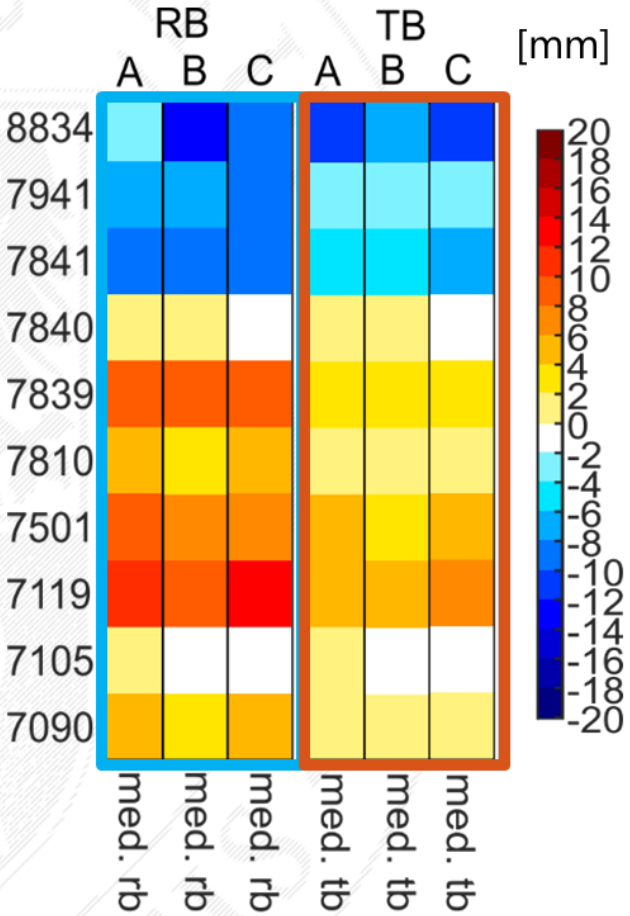
7-day → Determination of SLR station coordinates based solely on SLR to SWARM satellites and multi-satellite combinations

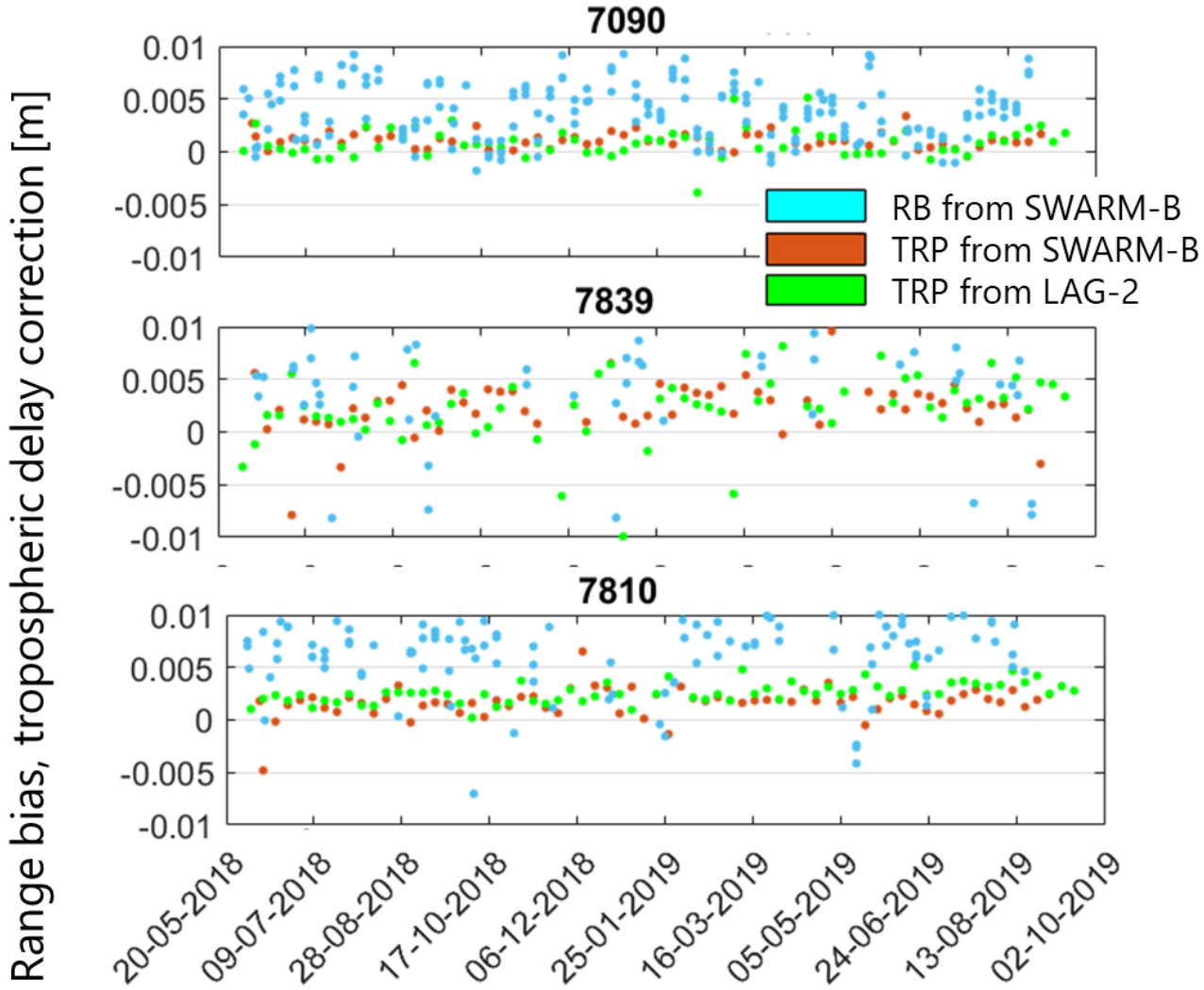
- no-net-translation/rotation network constraints
- comparison with **LAG**EOS-1/2-based solution

Processing:

- Mendes and Pavlis (2004) model and Mendes et al. (2002) mapping function for a priori troposphere
- Range bias- station-satellite daily correction/ long-term correction
- Tropospheric bias – daily correction/7-day correction
- 2018.42–2019.67 period, 1-day/7-day interval

Comparison of estimated correction parameters



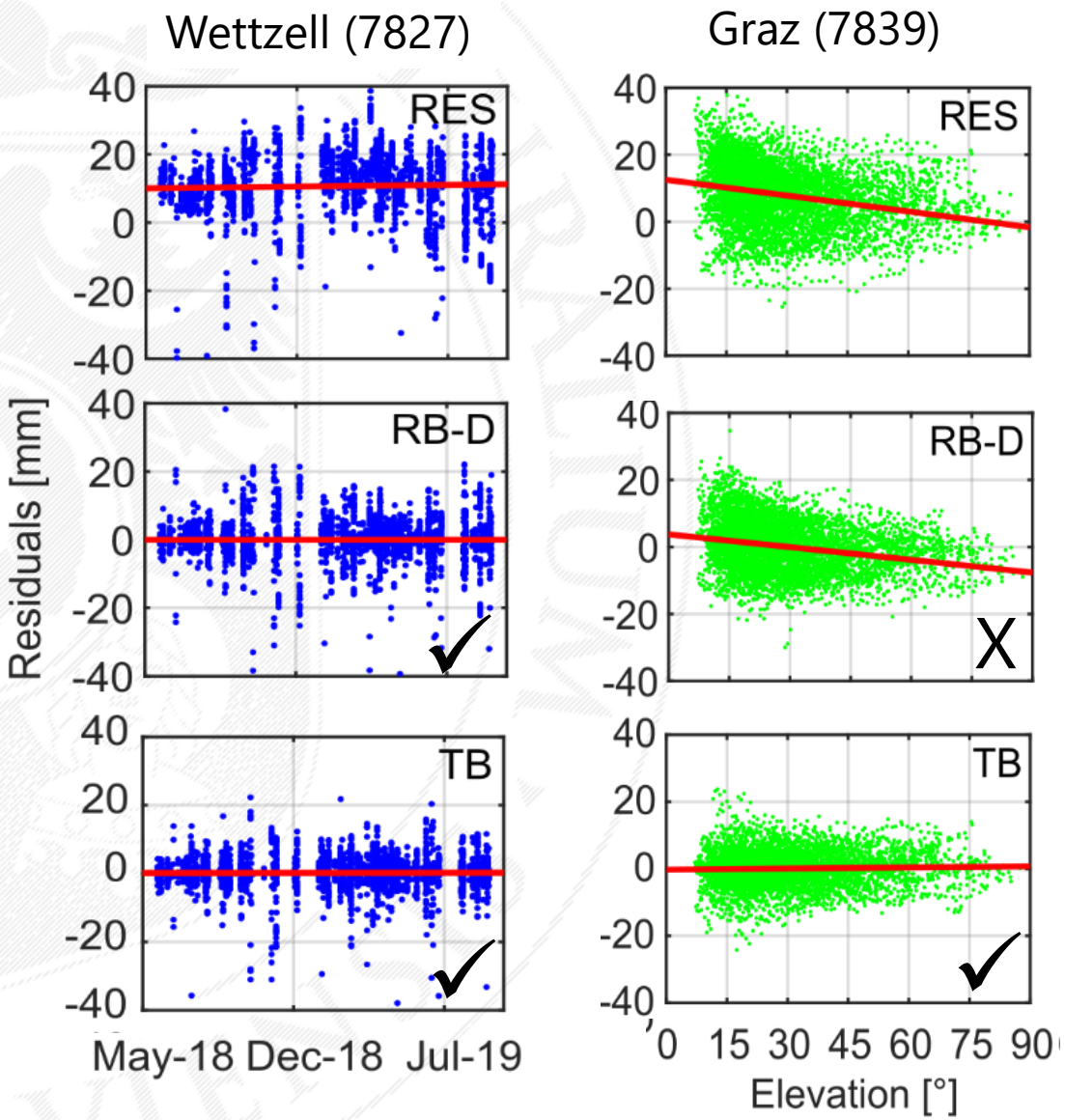


Range biases (**RB**) are more scattered than tropospheric corrections within the range of +/- 15 mm.

Troposphere biases (**TRP**) are analogical but less scattered within the range of +/-8 mm.

Troposphere corrections (**TRP**) from SWARM solutions are consistent with LAGEOS based corrections.

SLR validation– reduction of systematic effects in SLR residuals



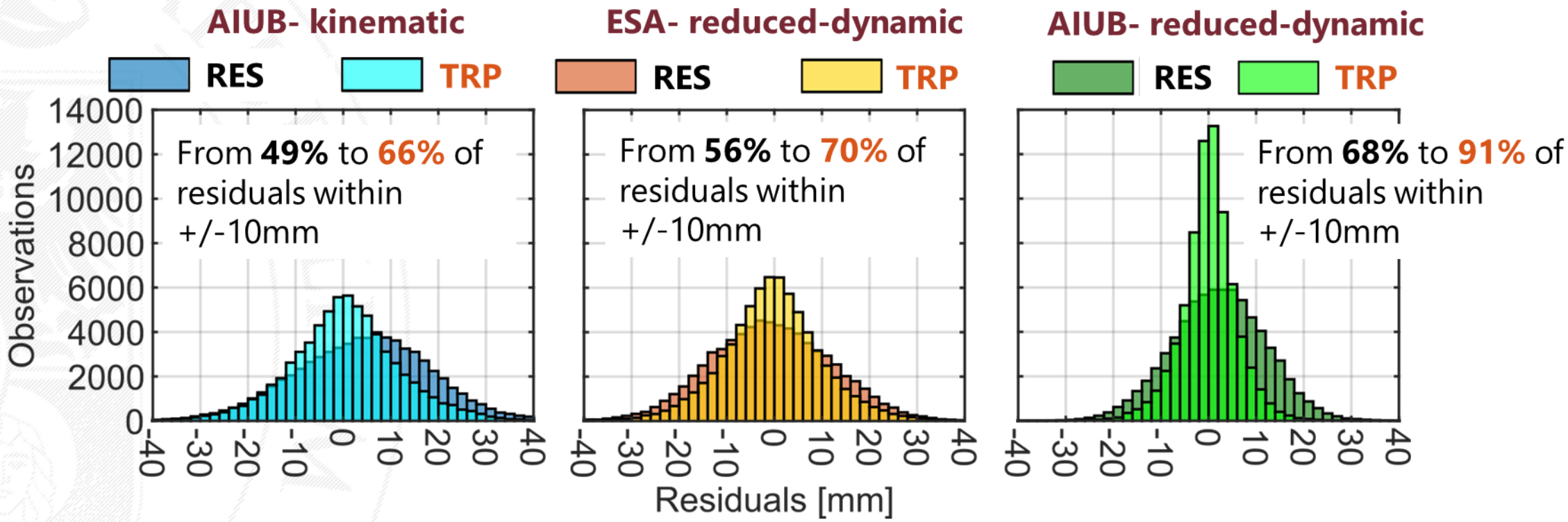
No modeling of systematic effects (**RES**) – offsets and dependencies

Range biases (**RB**) reduce only the mean offset of residuals

Troposphere biases (**TRP**) reduce the offset of residuals, the dependency of residuals to elevation angle, and the spread of residuals.

AIUB reduced-dynamic orbits SWARM-B example

SLR to SWARM-B – SLR residuals to different orbit solutions

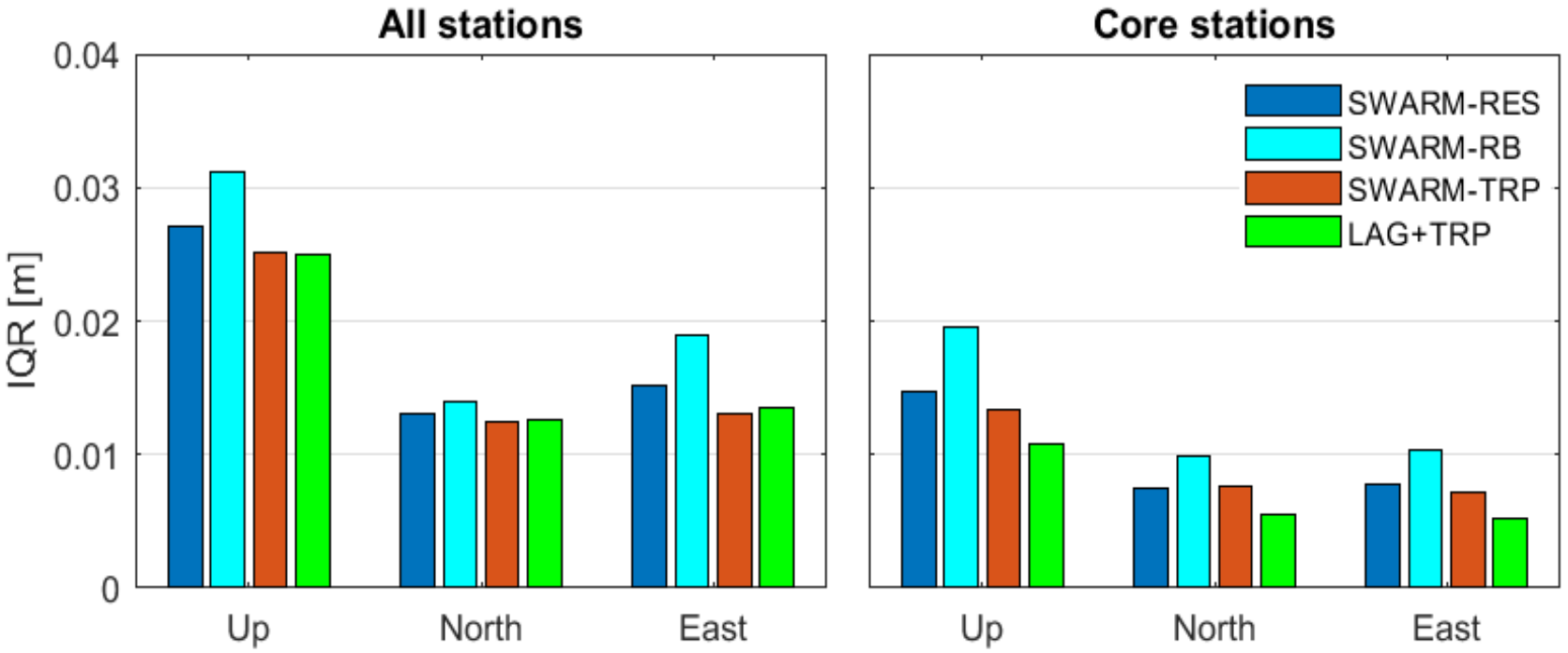


In **TRP**, SLR observations are more consistent with different orbit solutions.

Introducing troposphere biases allows for the comparison of the orbit quality between kinematic and reduced-dynamic orbits as SLR observations are freed from elevation-dependent errors.

SWARM-B example, Ten high-performing SLR stations

Station coordinates based on SLR to SWARM satellites



Considering troposphere bias correction instead of range bias **improves the repeatability station coordinates.**

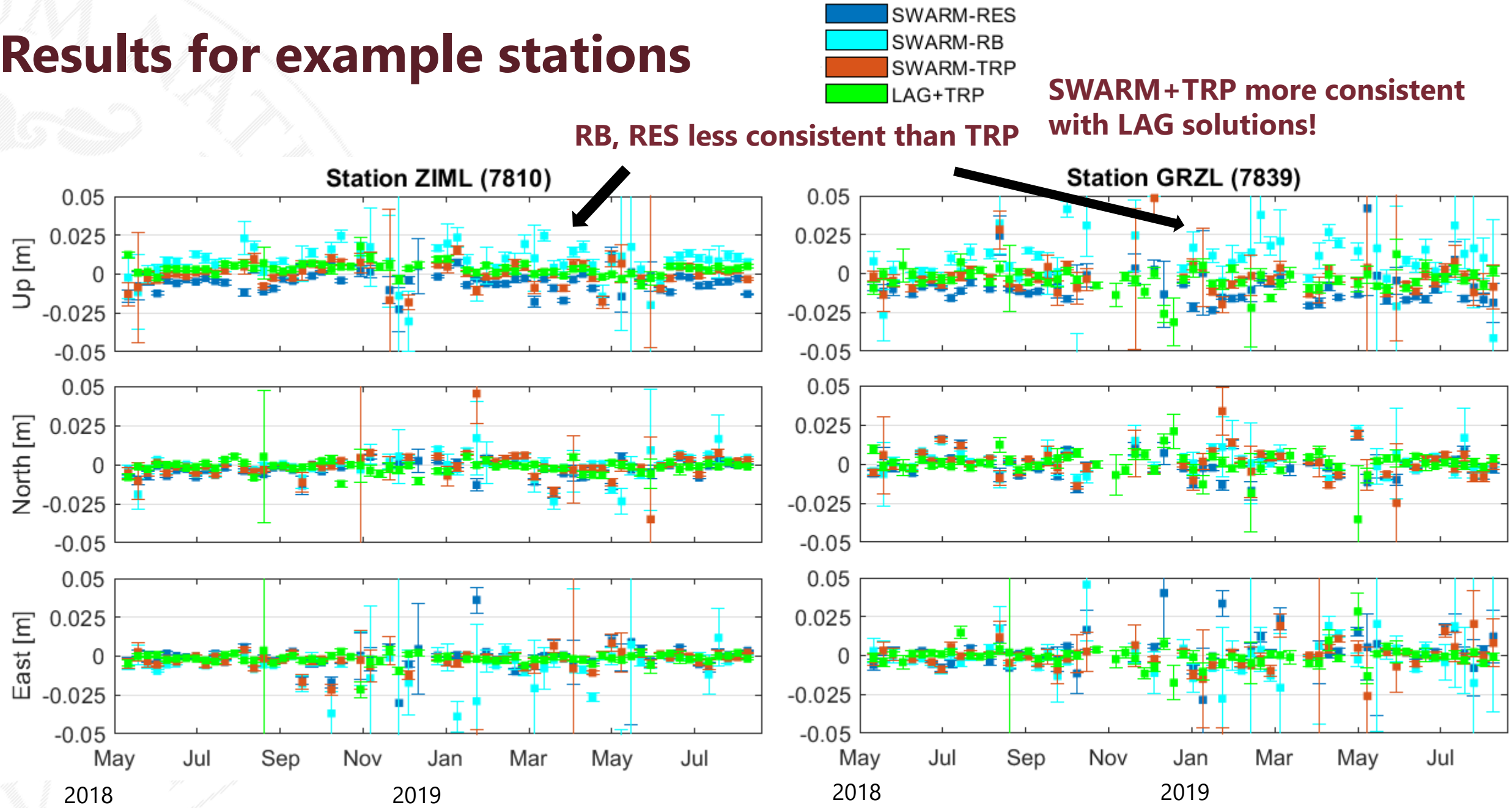
Repeatability of SLR station coordinates based on only SWARM satellites is at the level of less than 13 (25) and 7 (13) mm IQR for the Up and horizontal components, respectively.

SWARM-based solutions show 1-3 mm consistency with LAGEOS based solutions.

IQR - interquartile range w.r.t SLRF2014

All: 32 stations, core list: Yarragadee, Greenbelt, Matera, Hartebeesthoek, Haleakala, Zimmerwald, Mt Stromlo, Graz, Herstmonceux, Potsdam

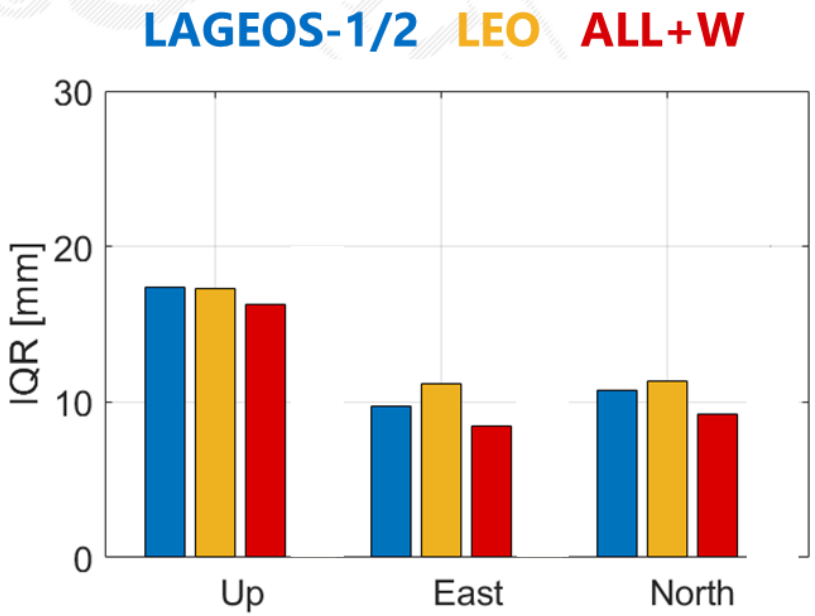
Results for example stations



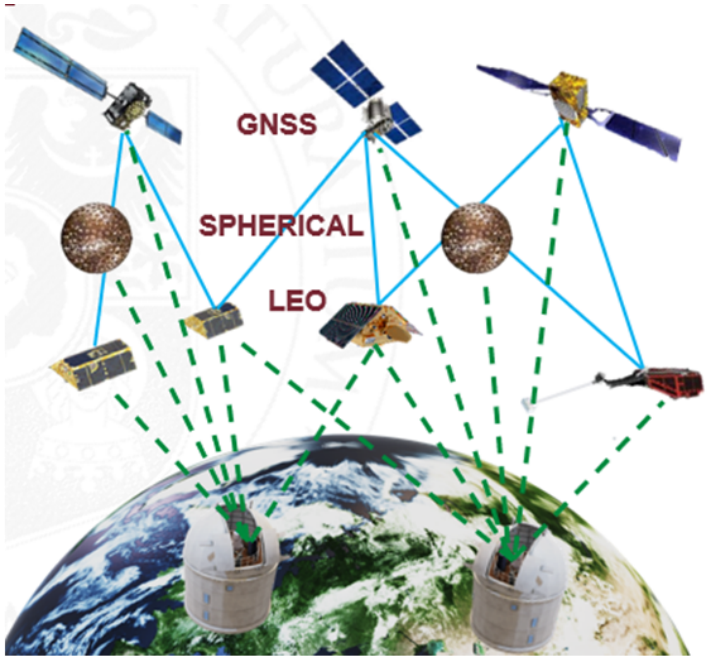
Multi satellite combination – station coordinates

SLR to single-LEO satellites,
multi-satellite combinations:
LEO (9, with SWARM-ABC)
+ spherical (3)+ Galileo (13),
fixed orbits of satellites,
weighting of observations,
1 year period + range bias

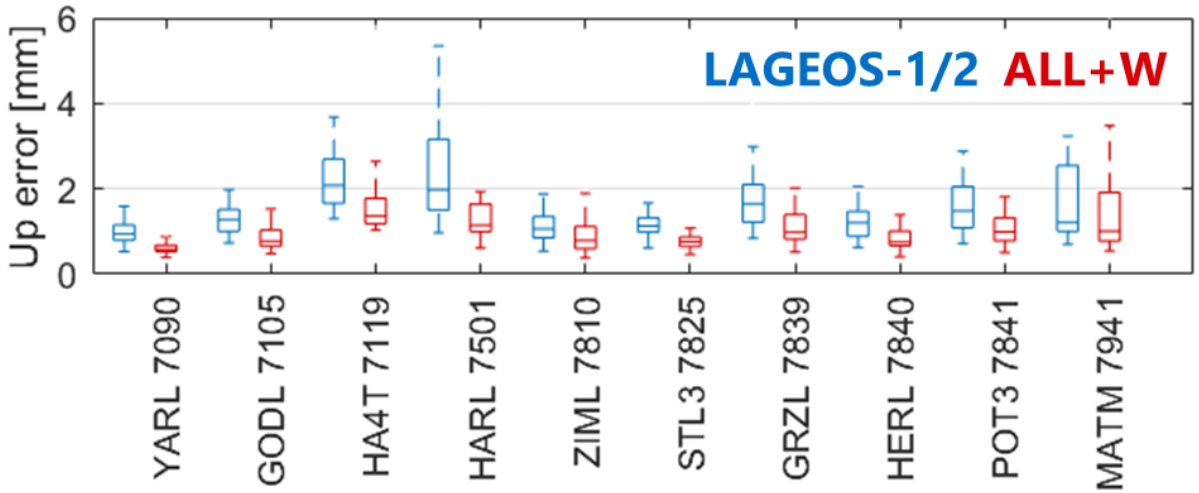
Multi satellite combination – station coordinates



SLR to single-LEO satellites, multi-satellite combinations: LEO (9, with SWARM-ABC) + spherical (3)+ Galileo (13), fixed orbits of satellites, weighting of observations, 1 year period + range bias



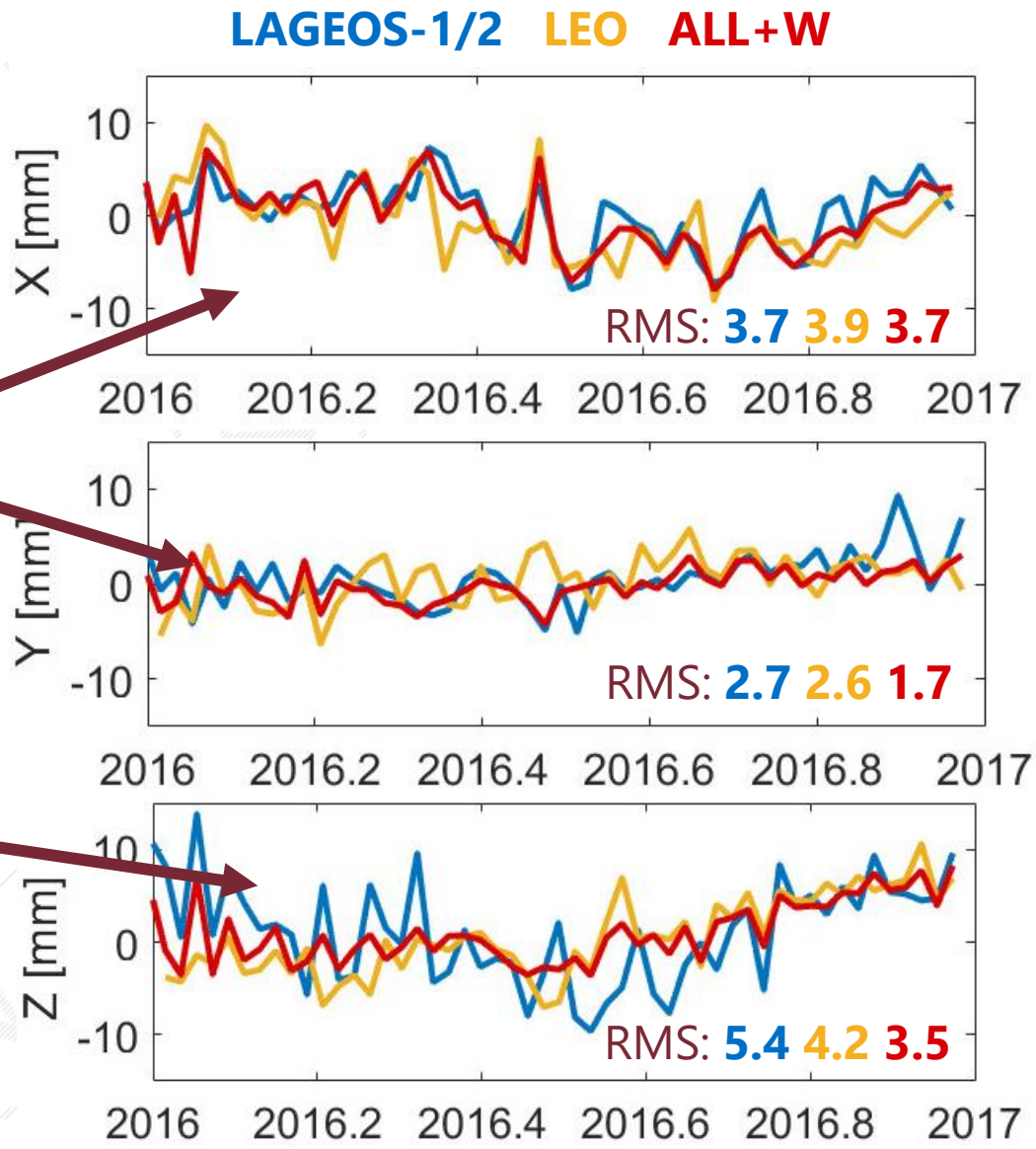
The positioning of **all (core)** SLR stations from **combinations** with the accuracy at the level of **less than 18 (10) mm for the Up and 10 (7) mm for the horizontal**



The coordinate **formal errors of ALL+W** in terms of median and interquartile ranges are **reduced by even 50%,** w.r.t. the LAGEOS, i.e., 1-mm level

IQR- interquartile range

Multi satellite combination – geocenter



Combinations consistent with LAGEOS

The annual signal is recovered

Geocenter motion can be derived **from SLR to LEO**s-only solutions and **multi-satellite combinations**

Summary

Modeling of systematic effects in SLR observations to Swarm (and other LEO) satellites…

…, i.e., station-satellite range biases, reduces the offset of residuals and the deficiencies in the determination of SLR station coordinates.

…, i.e., tropospheric biases, comprises not only deficiencies in tropospheric modeling, but also other elevation-dependent effects. Approach even further reduces the LEO residuals and allows for the comparison of the LEO POD quality.

… enables determination of the SLR station coordinates with repeatability at the level of 10-13 and 7 mm, for the Up and horizontal components (Swarm-only, multi-satellite combinations).

… enables determination of the geocenter, pole coordinates, and length of day (multi-satellite combinations). The estimates show the high-consistency with the LAGEOS-only solutions and the IERS products and benefit from introducing observations to different satellites.

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Thank you for your attention!

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