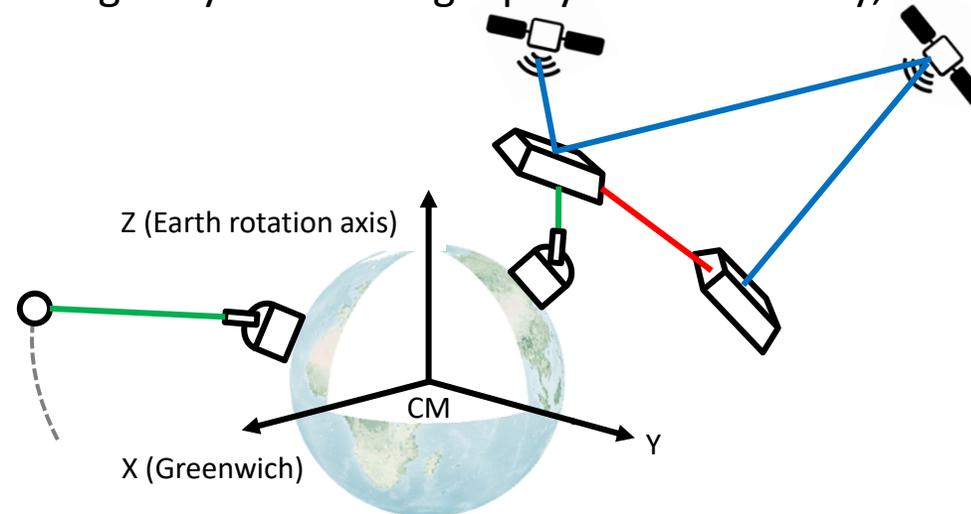


On the extension of geodetic parameter determination from SLR to spherical satellites by GNSS and SLR observations to non-spherical LEOs

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Motivation

- Satellite Laser Ranging (SLR) to spherical satellites is a well-established tool in reference frame determination.
- LEO (Low-Earth Orbiter) satellites equipped both with GNSS (Global Navigation Satellite System) antennas and laser retroreflectors enable the combination of these two space geodetic techniques, and thus, can serve as so-called **space ties**.
- Taking the example of the two **GRACE Follow-On** LEO satellites **GPS carrier phase** observations and **SLR** observations can be **combined** to derive **dynamic orbits** from two space geodetic techniques. Together with SLR observations to the spherical geodetic satellites, **geodetic parameters** can be derived. In this case, the two GRACE Follow-On satellites act as a space tie connecting the SLR and GPS observations techniques, and the geodetic parameters serve as global ties.

Data Sources and Satellites Used

Satellite Laser Ranging (SLR):

- to spherical SLR-dedicated satellites: LAGEOS-1/2 (part of the ILRS SLR contribution to ITRF realizations)
- to non-spherical satellites: GRACE-FO C+D (so far for orbit validation)

Facts for year 2019:

- SLR observations to LAGEOS-1/2: 200/day
- SLR observations to GRACE-FO C+D: 100/day



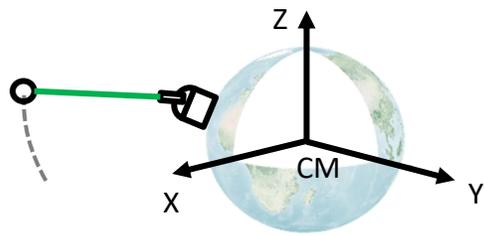
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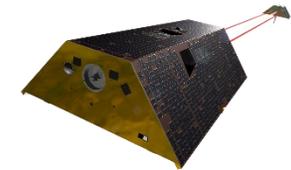
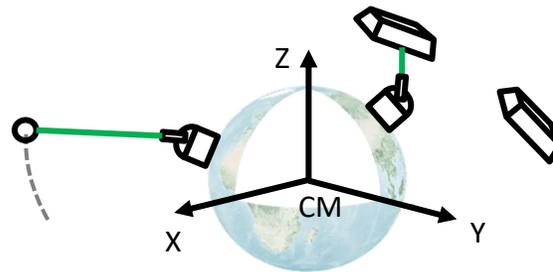
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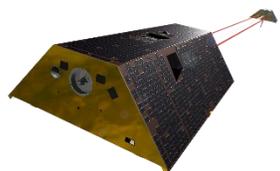
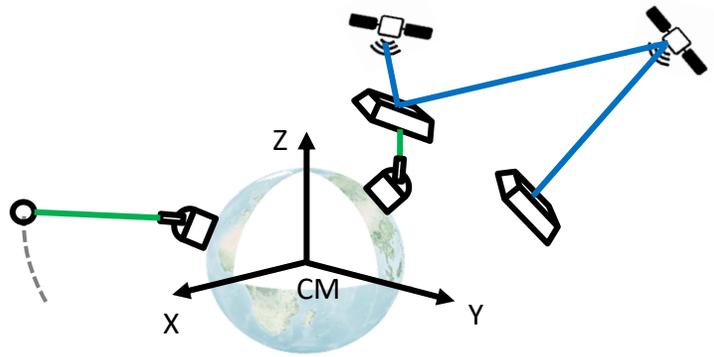
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Global Positioning System (GPS):

- from satellites GRACE-FO C+D

Facts for the year 2019:

GPS observations at GRACE-FO C+D: >100 000/day



Data Sources and Satellites Used

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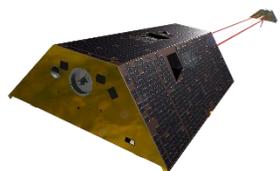
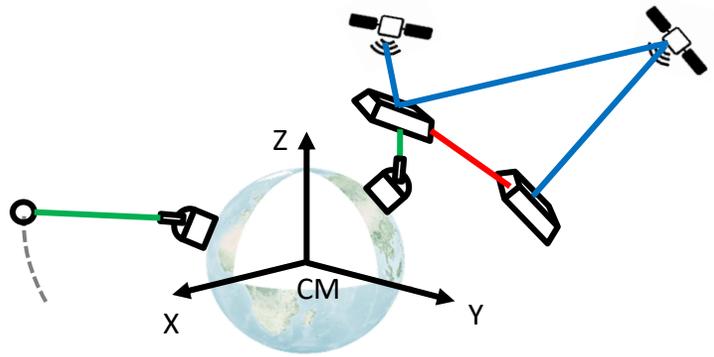
- from satellites GRACE-FO C+D

Facts for the year 2019:

GPS observations at GRACE-FO C+D: >100 000/day

K-band Observations:

- between satellite pair GRACE-FO C+D
- used for independent validation (relative)



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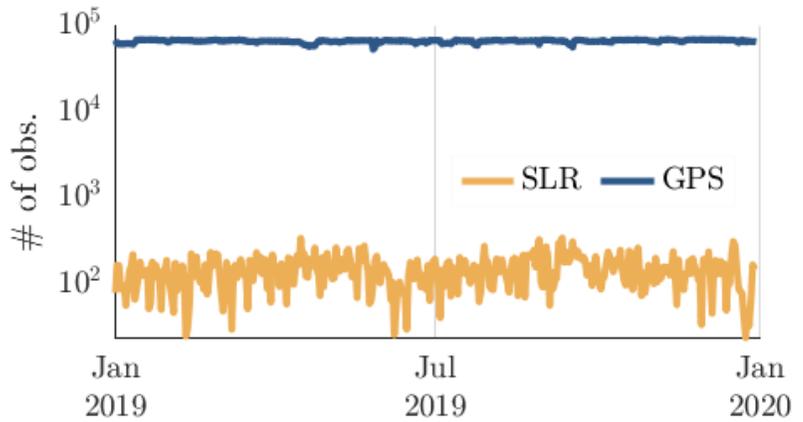
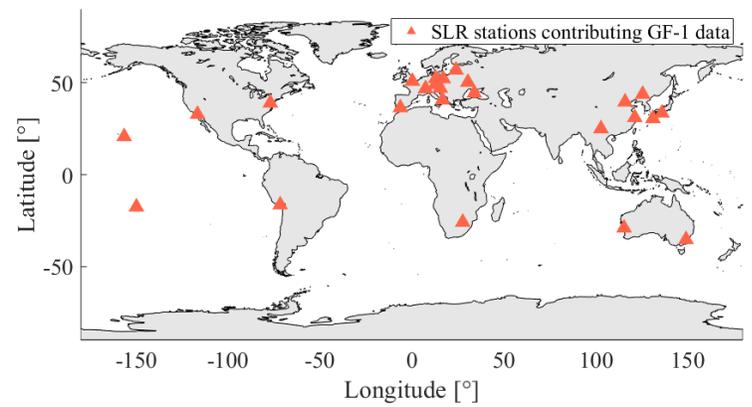
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Modelling and Parametrisation

Orbit parametrisation

- 7-day arcs for LAGEOS
- 1-day arcs for GRACE Follow-On
- 6 Keplerian elements at t_0
- constant acceleration in along-track (S)
- 1/rev in along-track (S_s, S_c) and cross-track (W_s, W_c) [sine / cosine]

Further parameters

- epoch-wise receiver clocks (for GPS)
- GPS carrier phase ambiguities (float)
- SLR station coordinates
- SLR range biases (RB)
- Earth rotation parameters (ERPs)
- geocentre coordinates (GCC)

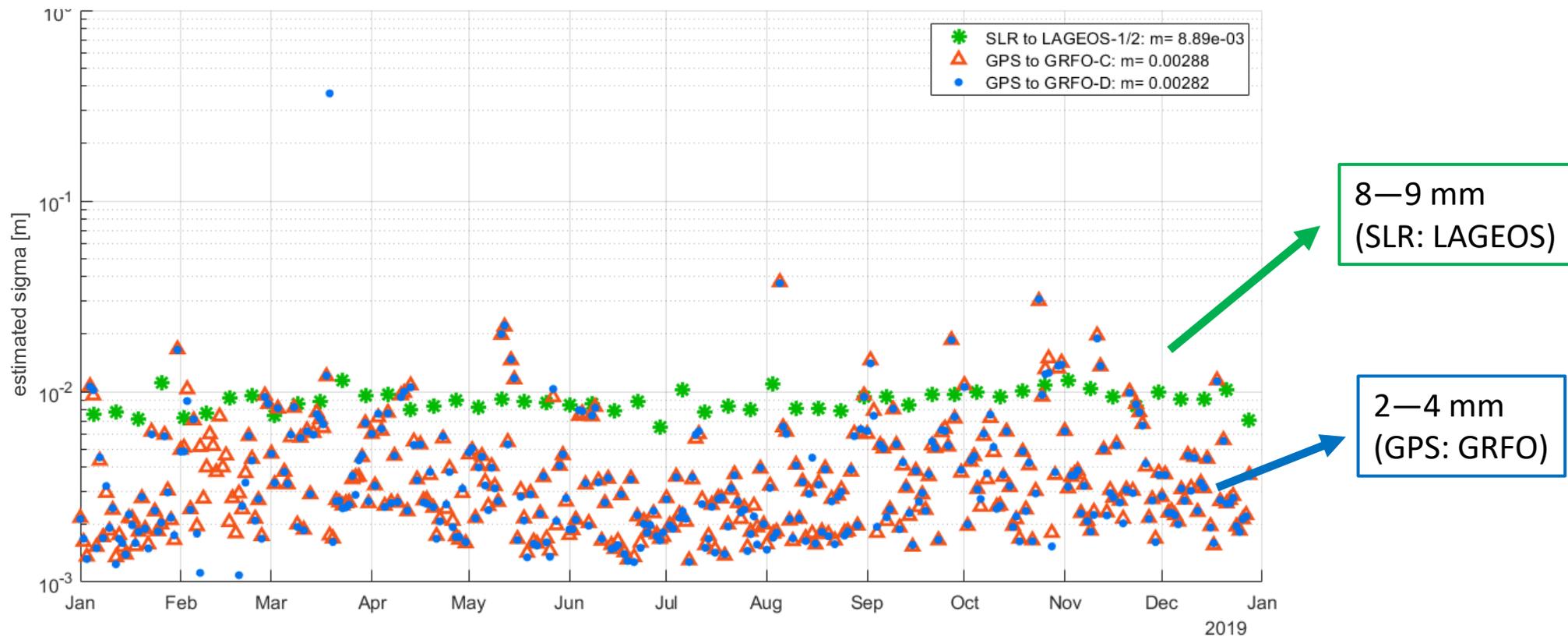
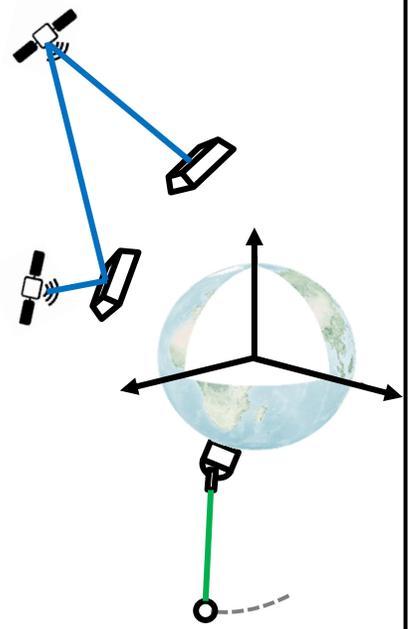
Background modelling

Models	Description
Earth gravity field	EIGEN-GRGS RL05: d/o 120 (Lemoine et al. 2023)
Third-body attraction	Moon, Sun, Venus, Mars, Jupiter Ephemeris: JPL DE405 (Standish 1998)
Ocean tide model	FES2014b: d/o 100 (Carrere et al. 2016) + admittances
Earth Tides	Solid Earth tides, pole tides and ocean pole tides: IERS 2010 ²
Loading corrections	Ocean tidal loading: FES2014b Atmospheric tidal loading: Ray and Ponte (Ray and Ponte 2003)
De-aliasing products	Atmosphere & ocean RL06: d/o 100 incl. S1- and S2-atmosphere tides (Dobslaw et al. 2017)
Relativistic Corr.	Schwarzschild Lense-Thirring deSitter
SRP ³ ERP ⁴ Air drag	Radiation pressure coefficient 1.13 Albedo reflectivity and emissivity NRLMSISE-00 (only for LEOs) (Picone et al. 2002)
Reference frame ERP	ITRF2014 ⁵ IERS-14-C04 ⁶
Nutation model Subdaily pole model	IAU2000 (Mathews et al. 2002) DESAI: IERS 2010 ²



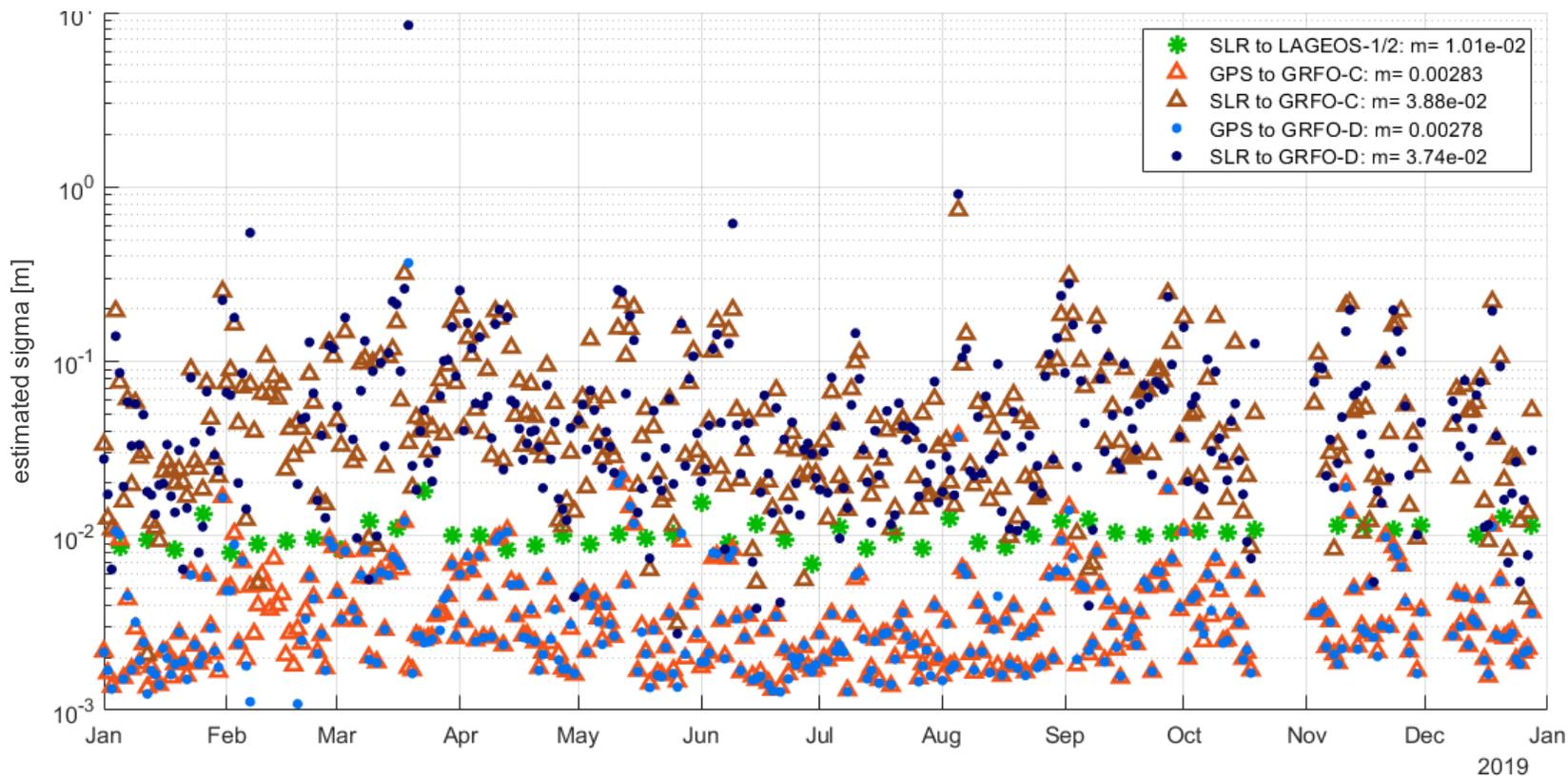
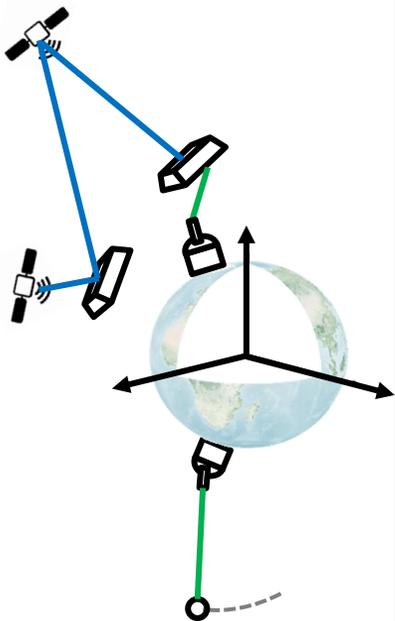
Relative Weighting

- Done with Variance Component Estimation (VCE)
– per satellite and arc



Relative Weighting

- Done with Variance Component Estimation (VCE)
 - per satellite and arc



20—40 mm
(SLR: GRFO)

10 mm
(SLR: LAGEOS)

2—4 mm
(GPS: GRFO)

Post-fit residuals (LAGEOS 1/2)

SLR only
LAGEOS only:
13.4 mm

SLR only
LAGEOS + GRFO:
21.4 mm

SLR + GPS
19.2 mm

- Results
 - SLR-only to LAGEOS-1/2 (reference)
 - median RMS of SLR ranging post-fit residuals

Post-fit residuals (GRFO-C)

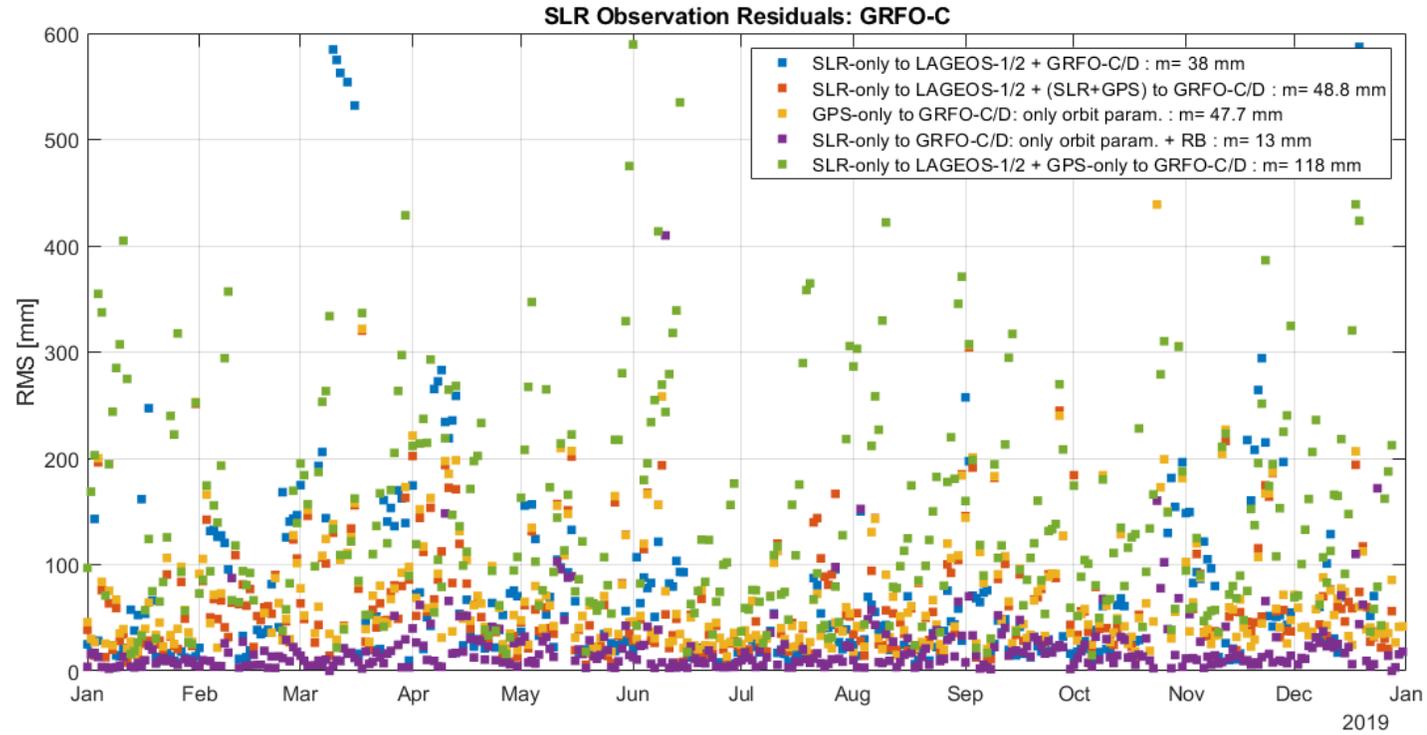
- SLR-only
- Combination
 - with LAGEOS
 - with GPS
- SLR validation of GPS-only orbit

SLR only
GRFO (orbit + RB):
13 mm

SLR only
LAGEOS + GRFO:
38 mm

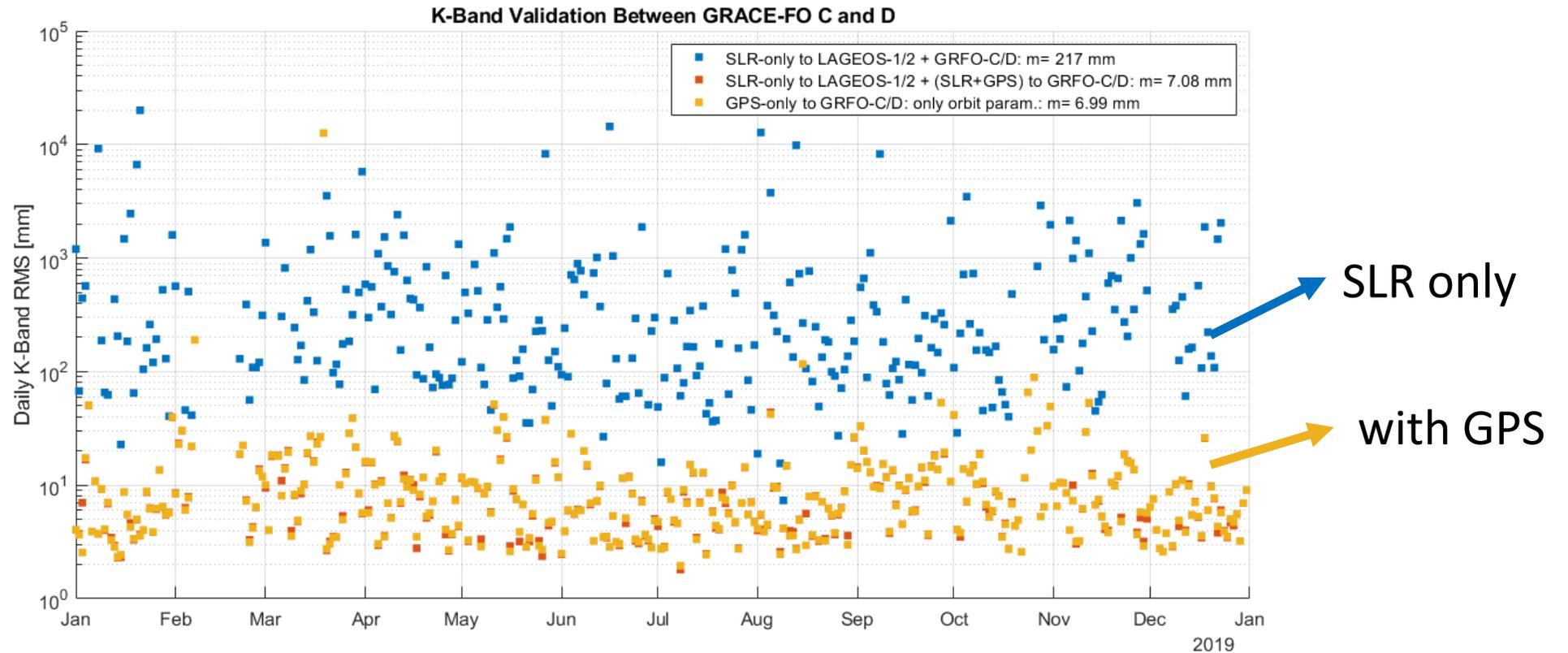
GPS only
(SLR validation)
orbit + clocks:
48 mm

SLR + GPS
LAGEOS + GRFO
49 mm



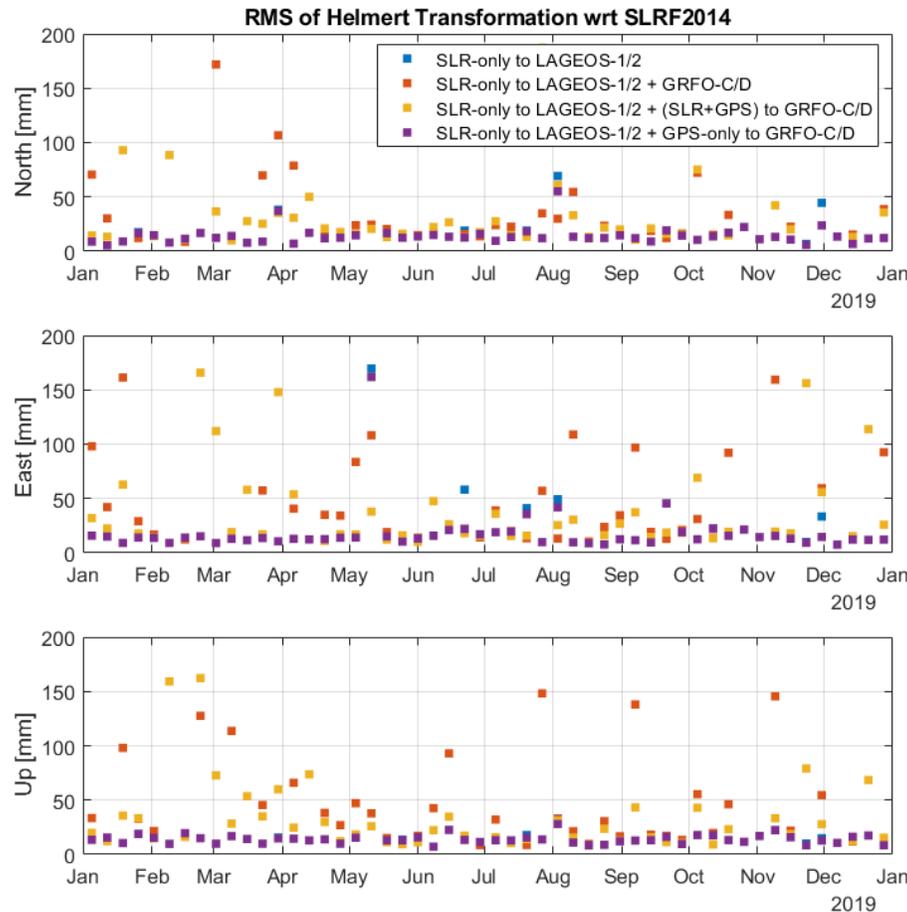
K-band validation

- Relative comparison of co-estimated orbits to KBR range measurements
- Two groups: SLR-only ~22 cm RMS (only few observations for POD)
 with GPS ~0.7 cm RMS

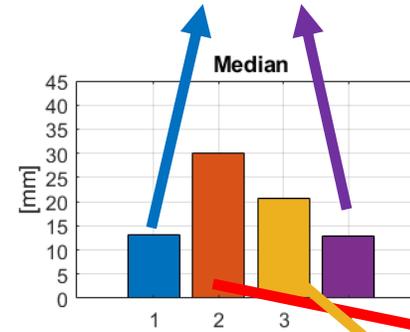


Station coordinates

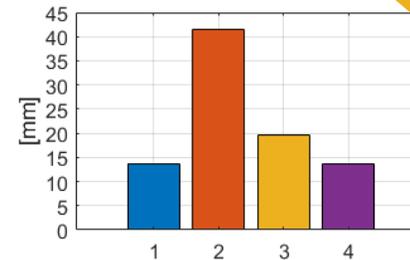
- Results for weekly coordinates
 - SLR-only to LAGEOS-1/2 (reference)



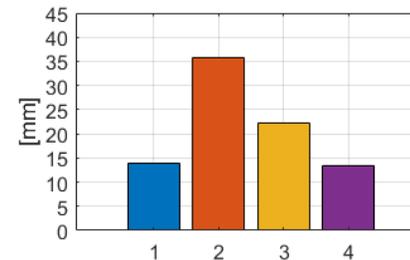
SLR only to LAGEOS
 GPS for LEO: no degradation through indirect effects



SLR to LEO added,
 no GPS: clear degradation

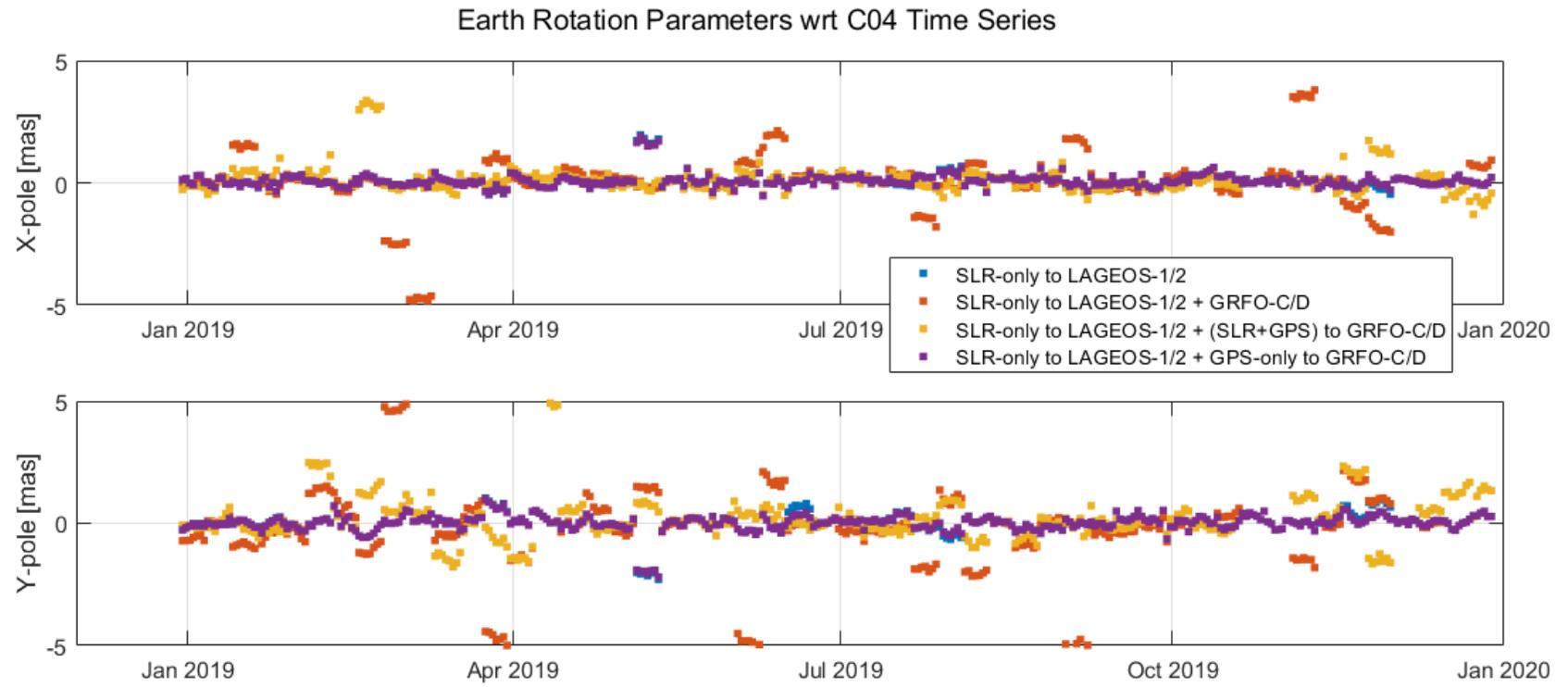


GPS and SLR to LEO:
 improves but not
 compatible with SLR only
 to LAGEOS



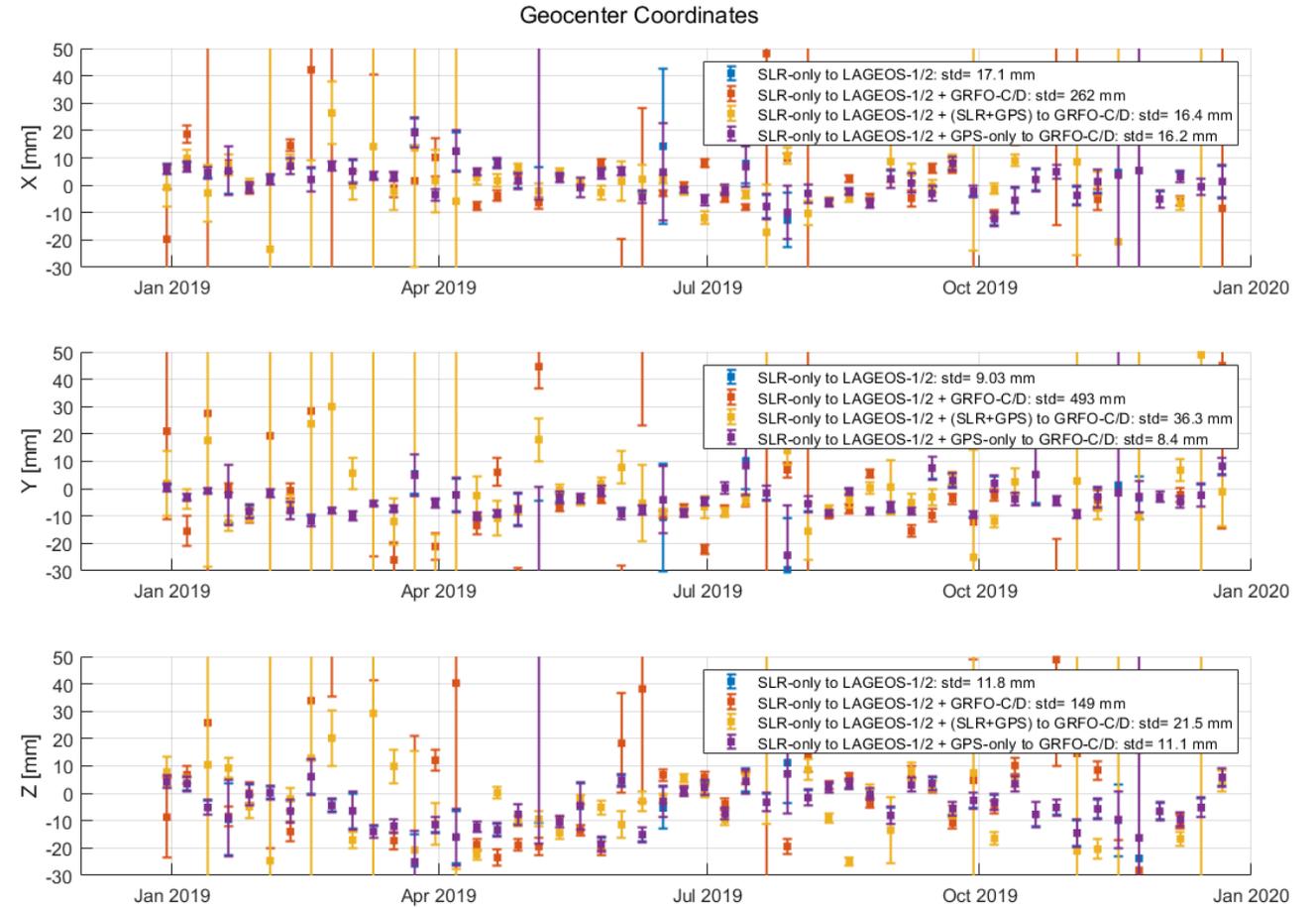
Polar Motion Parameters

- SLR-only to LAGEOS-1/2 (reference)
- Adding SLR to GRFO degrades solution compared to C04 series (red and yellow)
- Outlying weeks especially visible in Y-pole
- Only adding GPS for GRFO to SLR (LAGEOS only) has almost no impact (purple)



Geocenter

- Results for 7-day geocenter estimates
 - SLR-only to LAGEOS-1/2 (reference)
 - huge scatter as soon as SLR to GRFO is taken into account



Summary & Outlook

- Summary

- combining SLR to LEOs with GPS and SLR to spherical satellites works by from a technical perspective
- impact not yet fully understood. SLR to LEOs challenging for proper modelling
- weighting plays a crucial role. Automated methods work, however, impact is to be understood

- Outlook

- extension of the time span covered
- update to SLRF/ITRF2020
- including further LEOs (spherical and spherical) in the processing

Thank you for your attention!

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