WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

Modeling range corrections from SLR residuals to active Low Earth Orbiters – insights from study based on over 10 satellites and 20 years of data

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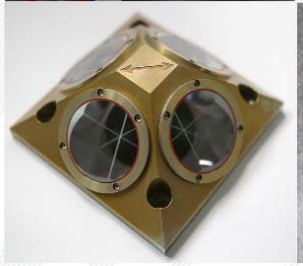
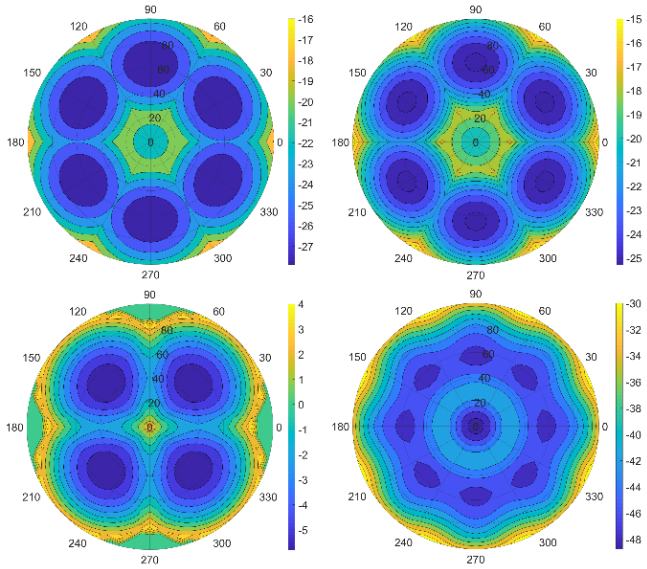
active Low Earth Orbiters (LEOs)

- variety of mission objectives: **gravity field**, **altimetry**, **magnetic field**, **temperature, wind speed**, **Earth's core dynamics**, **Earth's surface mapping (DEM)**
- different altitudes (260-1500 km), shapes, payload, orbit
- space geodetic techniques co-location: GNSS, SLR, DORIS
- current main contribution of SLR to LEOs: **validation of precise orbit (POD) products** derived by GNSS/DORIS
- satellite specific modeling requirements (mass change, LRA offsets/orientation)





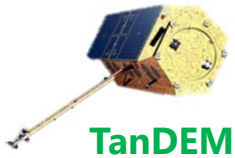
Sentinel-3AB

815

Swarm-B

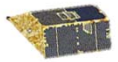
540

TerraSAR-X



TanDEM-X

514



GRACE-FO

500

CHAMP

474

Swarm-AC

460

GRACE

330-450

GNSS
LAGEOS

Altitude [km]

Motivation

1) **Most of normal points (NPs) provided by ILRS consider active Low Earth Orbiters** (e.g. Swarm, GRACE, Sentinel-3 missions)

2) **ILRS does not provide official range correction products for LEOs**

3) **Different approaches for modeling of systematic errors in SLR-based validation of LEO precise orbit products**

4) **Update of products** (ITRF2020, CM corrections, DHF, POD of LEOs)

Overview of approaches for bias handling in active LEO orbit validation

1) **correction types:** range biases // time biases // troposphere biases // other
2) **type:** station-satellite // station-satellite_group
3) **scheme:** SLR-based validation of LEO orbits // SLR(SLR+GNSS)-based POD of LEOs // in pre-processing and added as a priori
4) **time resolutions:** daily // weekly // monthly // yearly
5) **number of parameters:** only range biases // range biases + station coordinates // together with other parameters
6) **grouping of stations for analysis:** high-performing(core) stations // all stations // detector-depending groups // clustering of stations
7) **+** different outlier rejection, elevation angle threshholds

For details please see, e.g.: Arnold et al. 2019; Calliess et al. 2024; Exertier et al. 2017, 2018; Montenbruck et al. 2018; Li et al. 2023, 2024; van den IJssel et al. 2015; Saquet et al. 2024; Strugarek et al. 2019, 2021, 2022; Zajdel et al. 2023; Zhang et al. 2021; GMV reports;

ILRS recommendations for satellites other than LAGEOS/Etalon

1) DataHandlingFile(DHF)240213:

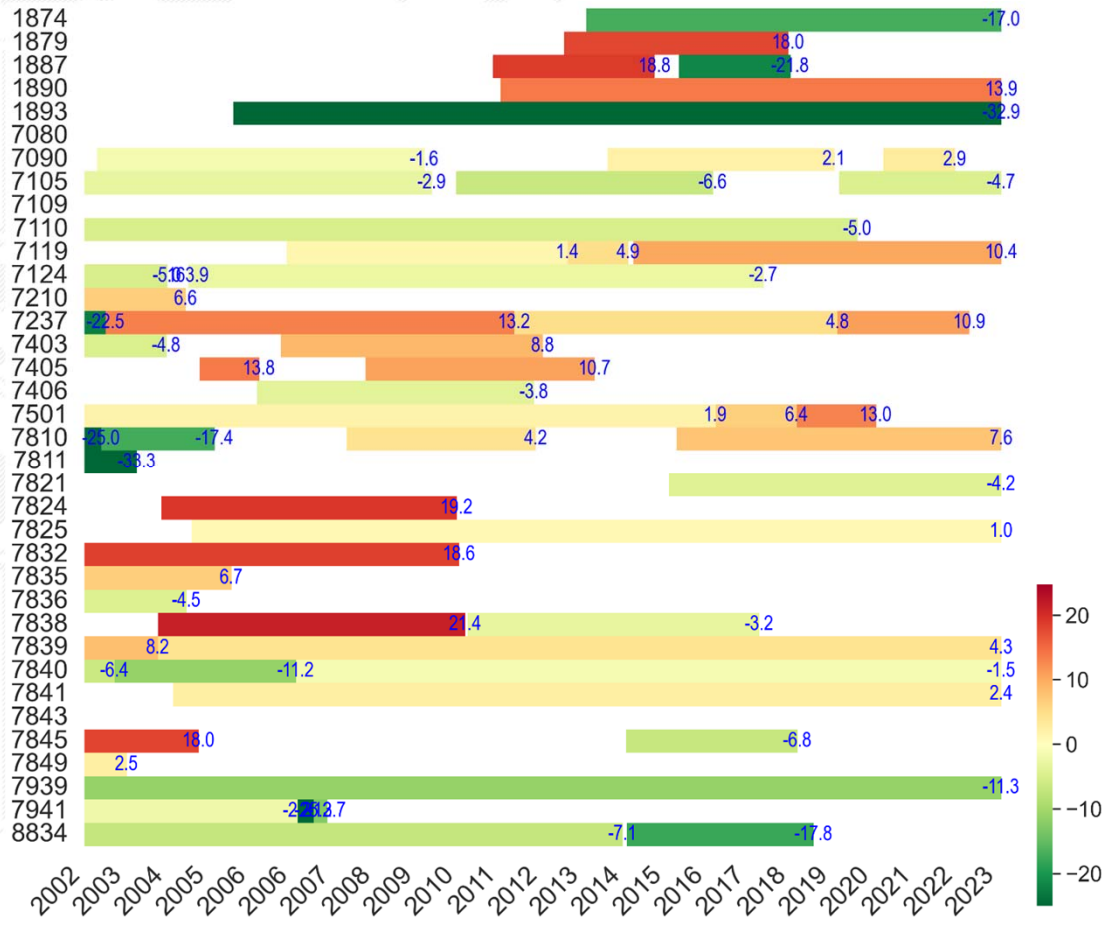
If an ITRF2020/SLRF2020 user performs POD on any satellites other than for LAGEOS 1/2 and Etalon 1/2 for which we have specific Model Bias values, a **station-specific range bias must be pre-applied, calculated as the mean of the two biases for the LAGEOS and LAGEOS-2 satellites**. This bias should be used only as an a priori value since additional satellite-specific errors might still be present (e.g. CoM errors, LRA offset/orientation errors).

2) M. Bloßfeld et al. (EGU, 2024):

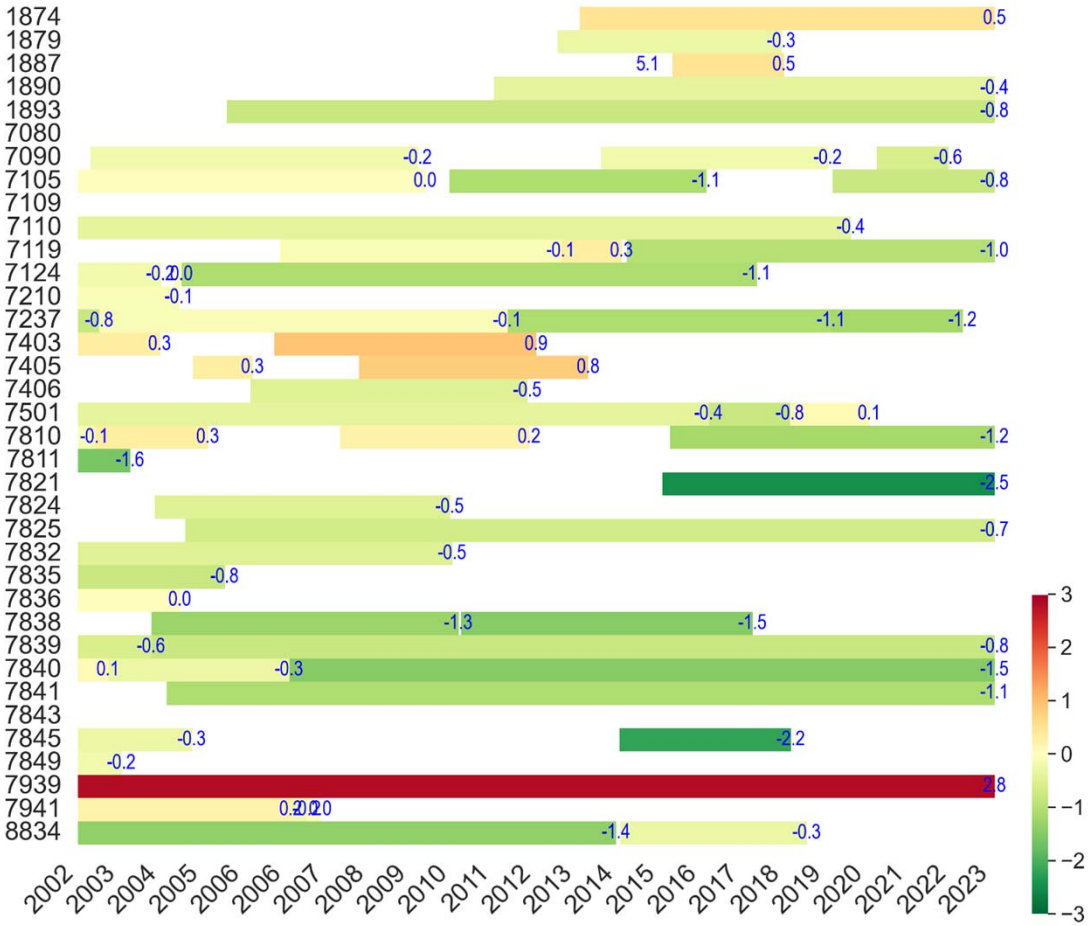
- ITRF2020: use PSD and periodic corrections (CM),
- use of CoM corrections and the most recent DHF
- **apply long term LA-1 mean range bias (pragmatic approach) or**
- **mean LA-1/2 long term-RBs as a priori and estimate (mean long-term) RBs**

Range bias (RB) corrections from DHF240213

Mean RBs LAG1 and LAG2 [mm]



RB difference between LAG1 and LAG2 [mm]



+MODEL/RANGE_BIAS section only

Data and processing solutions

12 LEO satellites: GRACE-A/B/FO1/FO2, Swarm-A/B/C, CHAMP, TanDEM-X, TerraSAR-X, Sentinel-3A/B

GNSS POD products provided by IFG University of Graz - Reduced-dynamic solution based on the raw observation approach (details: **Suesser-Rechberger B, et al. 2022**)
S3A/B orbits provided by TU DELFT, ESA – Reduced-dynamic solution (details: van den IJssel J, et al. 2015)

SLR data: Normal Points (crd ,.npt , .np2), station satellite info, processing models provided by ILRS, **(CDDIS, EDC TUM)**
ITRF2020 + PSD + CM, satellite CoM, LRA models

SLR orbit validation of LEOs with RB modeling
(all/high performing stations)

Bernese GNSS Software v.5.4 (Dach et al. 2015)

Mayer-Guerr, T., et al. (2021).

Suesser-Rechberger, et al.(2022). Improved precise kinematic LEO orbits based on the raw observation approach. Adv in Space Res, 69(10), 3559-3570.
van den IJssel J, et al. (2015) Precise science orbits for the Swarm satellite constellation. Adv Space Res 56(6):1042–1055.

Data and processing solutions

12 LEO satellites: GRACE-A/B/FO1/FO2, Swarm-A/B/C, CHAMP, TanDEM-X, TerraSAR-X, Sentinel-3A/B

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Bernese GNSS Software v.5.4 (Dach et al. 2015)

Mayer-Guerr, T., et al. (2021).

SLR orbit validation of LEOs with bias modeling
(all/high performing stations)

Tested solutions – residual analysis:
(0) no modeling of RB
(1) a priori mean RB from LAG1/2 (DHF)
(2) a priori mean RB from LAG1/2 (DHF)+ est. daily RB = est. daily RB
(3) a priori 30-day mean RB per station_LEO_group

(0) Unmodeled residuals

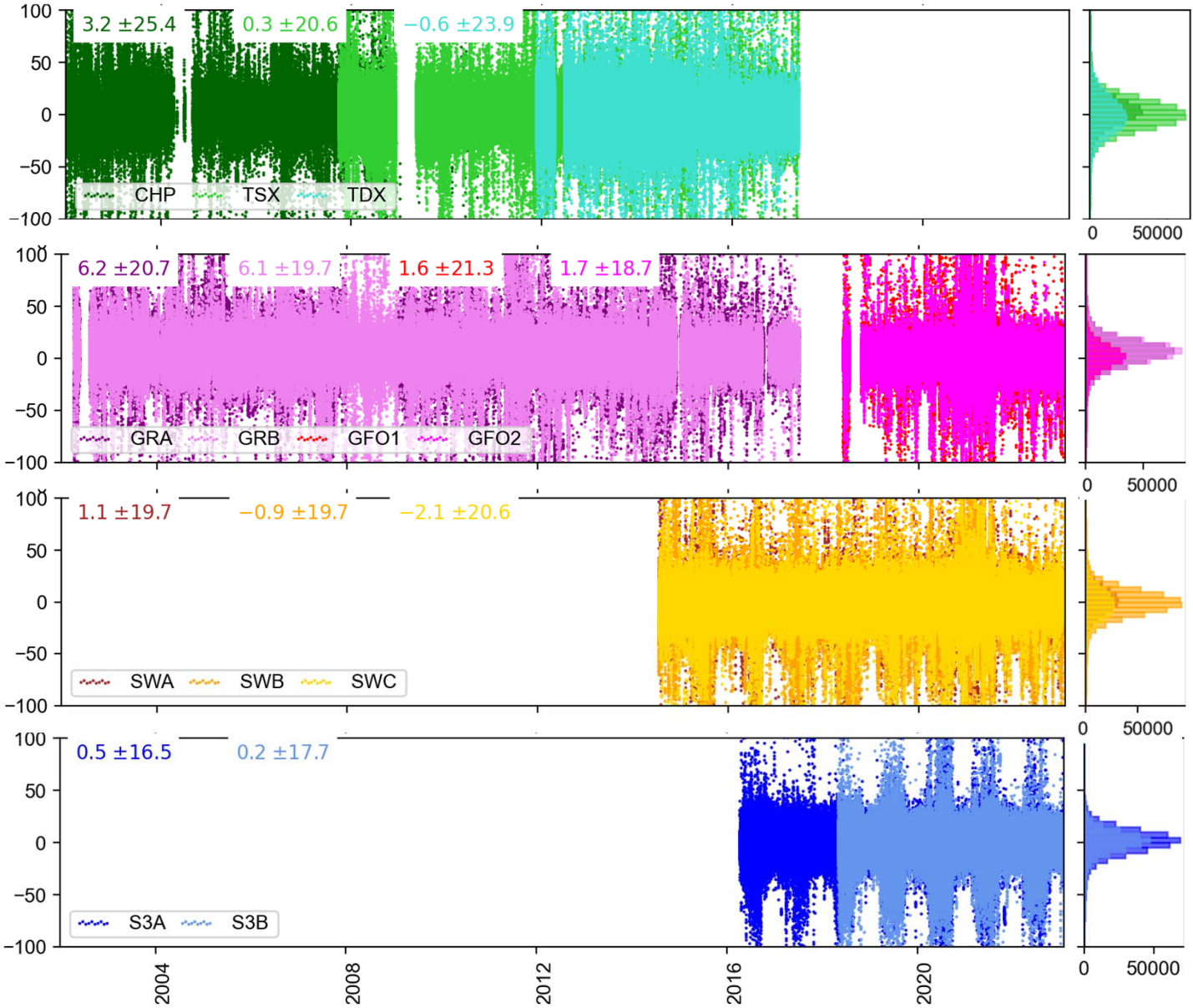
Period **2002.0-2023.1**

12 satellites, all stations

SLR residuals of GNSS POD products

~4 000 000 NPs

Offset of residuals at range of **+/- 0-6 mm, st.dev of 17-25 mm** (all stations)



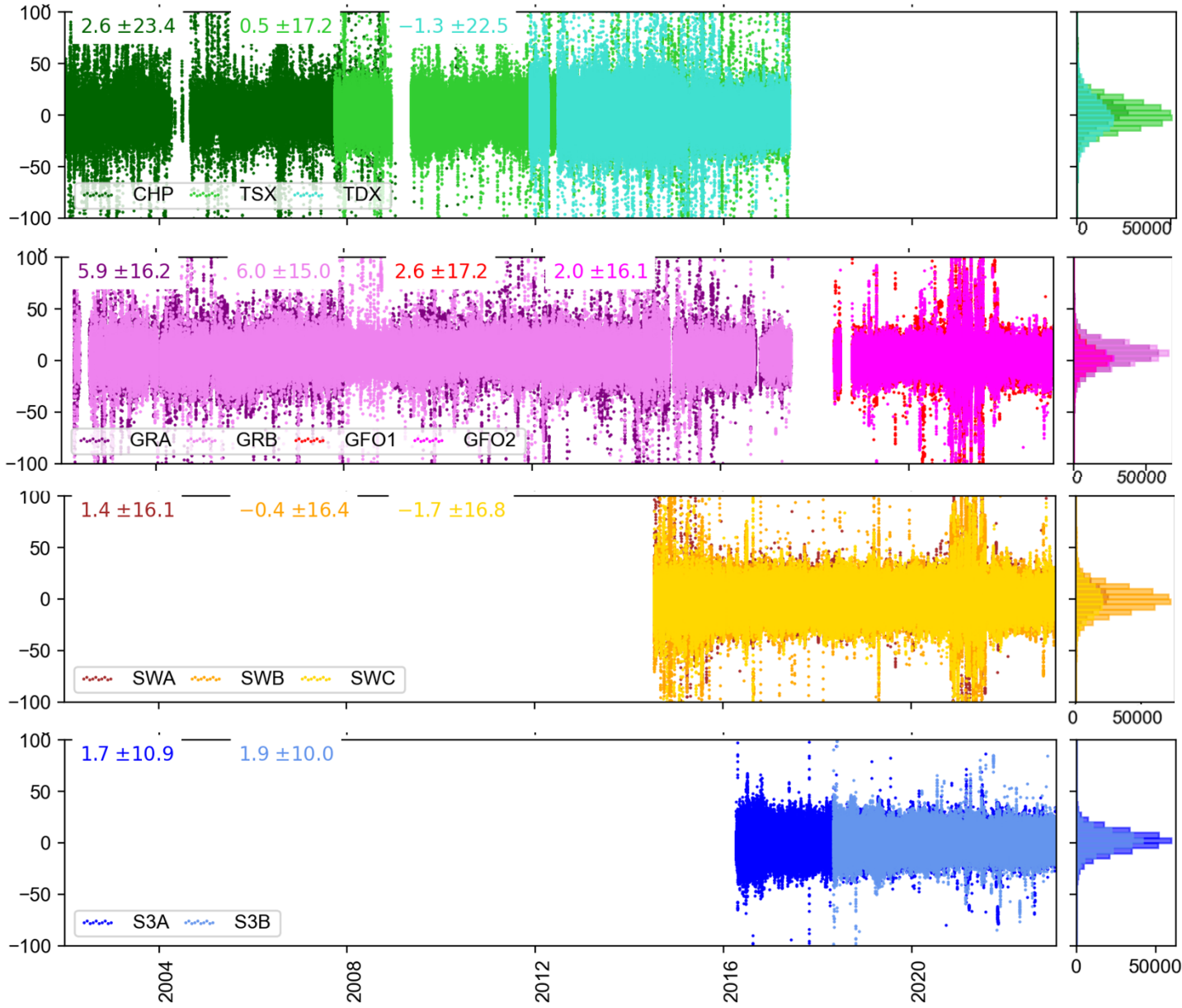
SLR residuals (mean+st.dev) [mm]

(0) Unmodeled residuals

12 satellites, high-performing stations (12):
7090, 7105, 7501, 7810, 7825, 7827, 7839, 7840, 7841, 7941, 7119, 8834

Offset of residuals at range of
+/- 0-6 mm, st.dev. 10-17mm

St. dev lower by 1-7 mm!



SLR residuals (mean+st.dev) [mm]

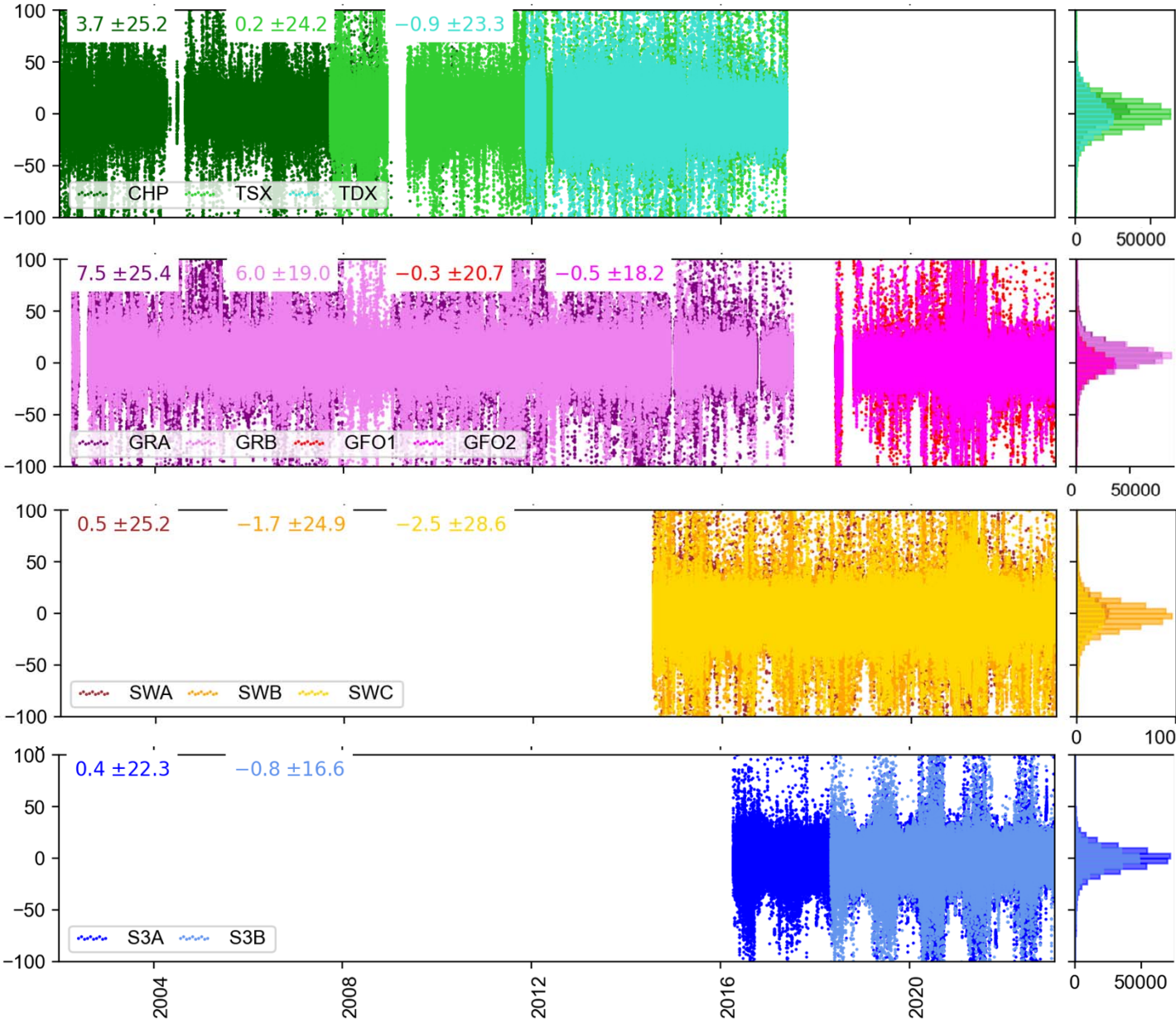
(1) a priori mean RBs from LAG1/2 (DHF)

12 satellites, all stations

Offsets of residuals at range of **+/- 0-7 mm, st.dev 17-28mm**

St. dev. increased by a few mm! for most of satellites (slighly reduced by 1-3 mm only for S3B, GRB, TDX) w.r.t (0)

SLR residuals (mean+st.dev) [mm]



(2) a priori mean RB from LAG1/2 (DHF)+est. daily RB = est. daily RB

Example output from:

a priori mean RB from LAG1/2 (DHF)+est. daily RB

=

est. daily RB

Range bias estimate:

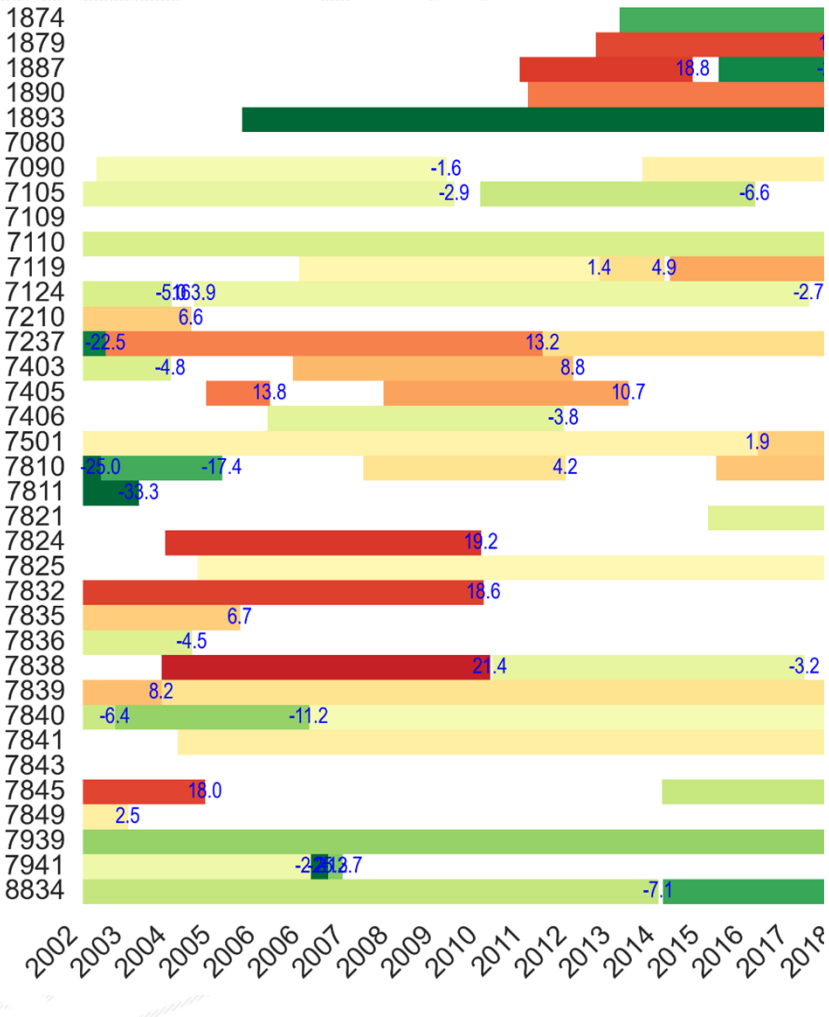
Station	Sat	Correction	Estimated value	RMS error	A priori value	Unit
7839 11001S002	965	0.00431	0.00861	0.00131	0.00430	meters
			=		≠	
7839 11001S002	965	0.00861	0.00861	0.00131	0.00000	meters

=

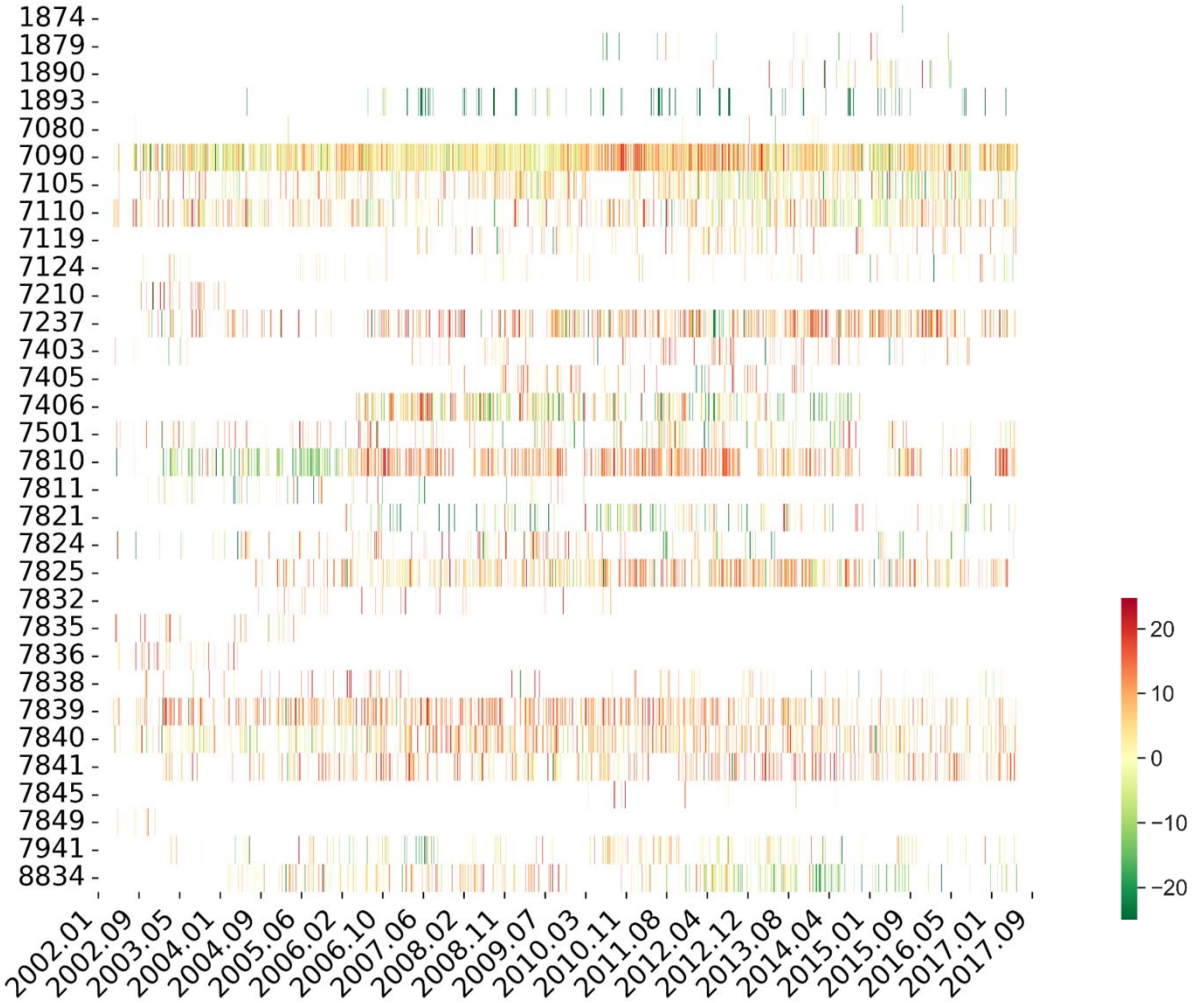
Identical solutions, and estimated range biases – identical validation results

(2) a priori mean RB from LAG1/2 (DHF)+est. daily RB = est. daily RB

Mean RBs LAG1 and LAG2 [mm]



GRACE-B daily RBs [mm]

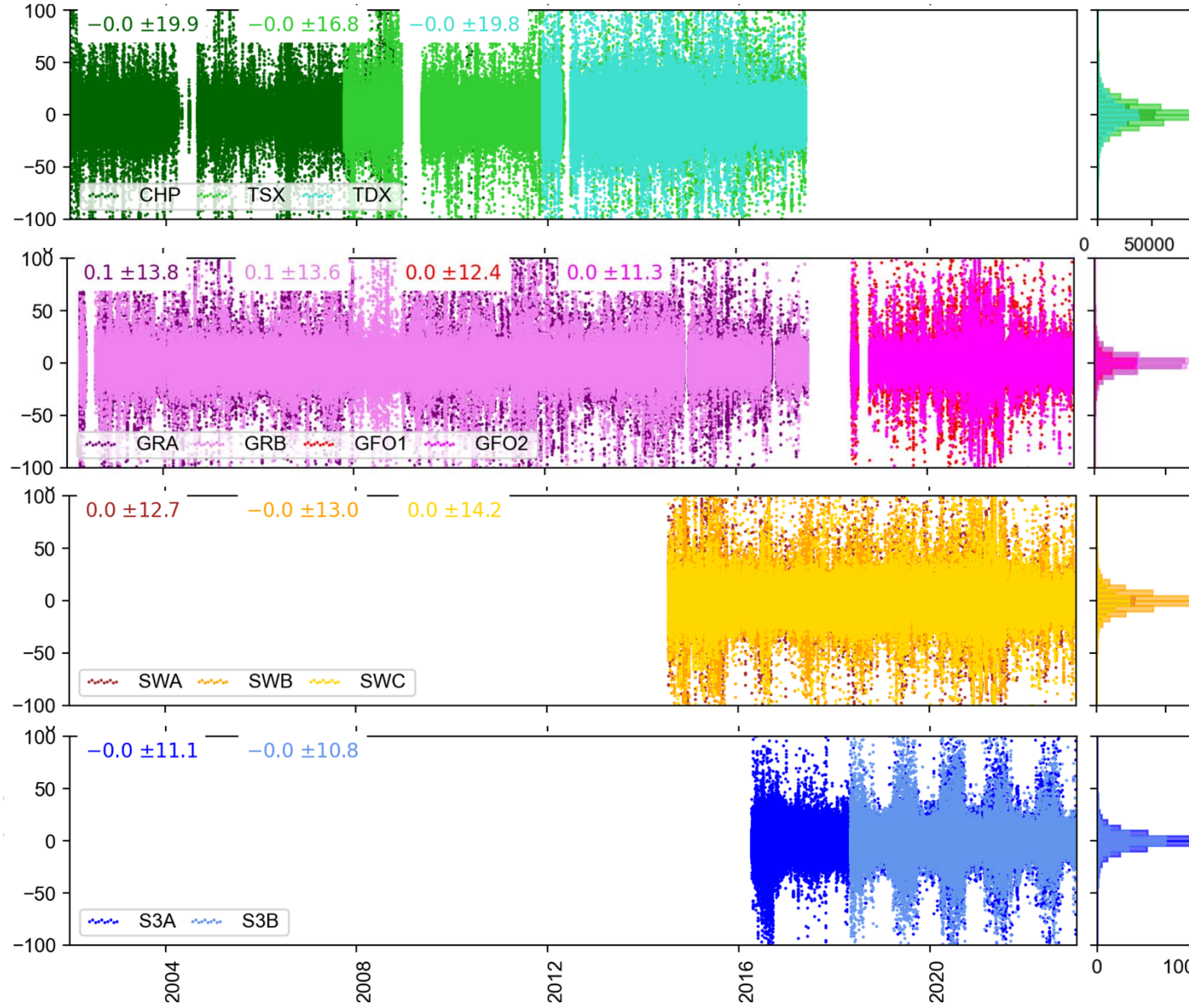


(2) a priori mean RB from LAG1/2 (DHF)+est. daily RB = <u>est. daily RB</u>

12 satellites, all stations

St. dev residuals at range of 10-19mm

St. dev. reduced by 2-7 mm and no offset!
w.r.t (0)



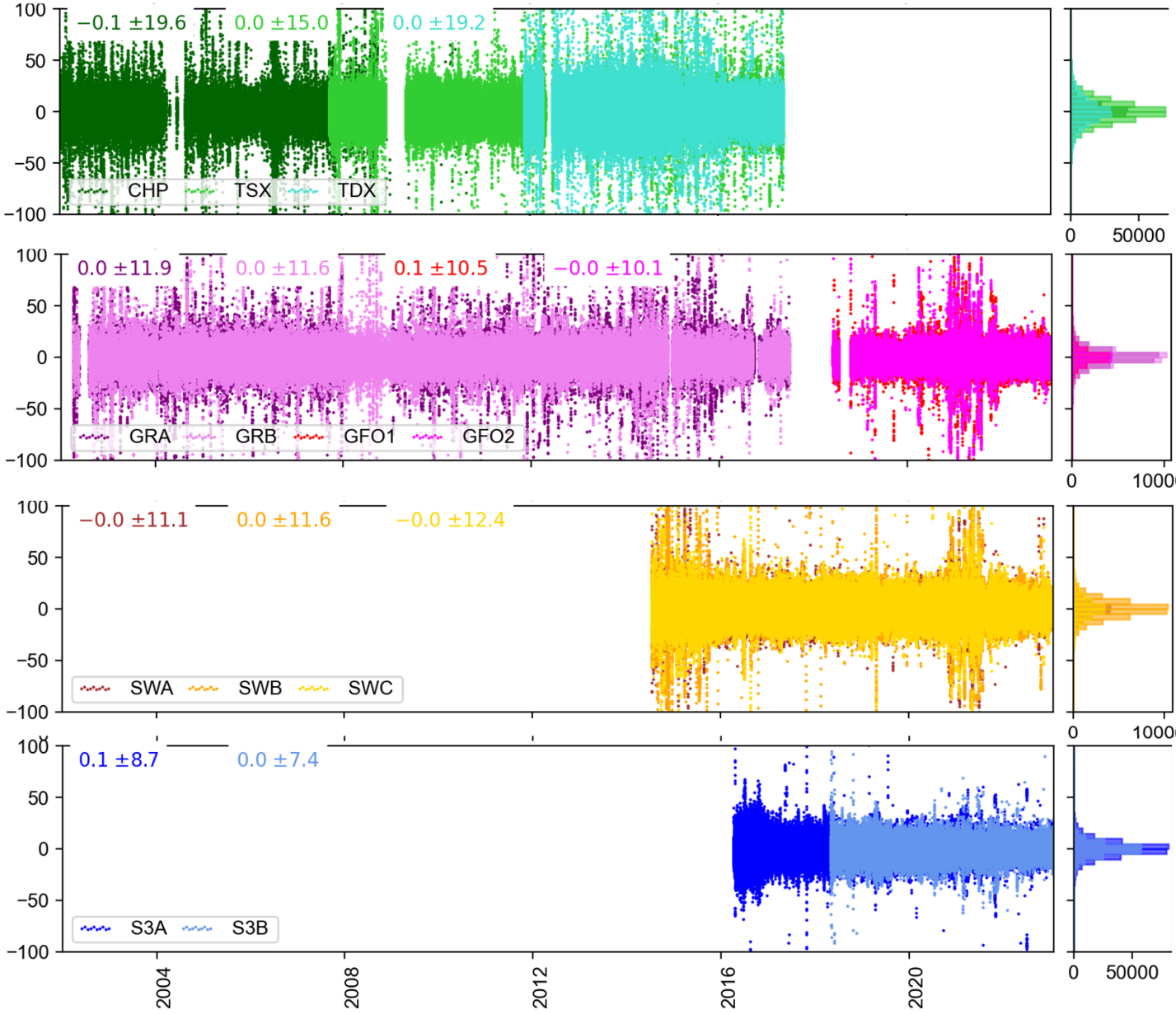
SLR residuals (mean+st.dev) [mm]

(2) a priori mean RB from LAG1/2 (DHF)+est. daily RB = <u>est. daily RB</u>

12 satellites, high-performing stations (12):
7090, 7105, 7501, 7810, 7825, 7827, 7839, 7840, 7841, 7941, 7119, 8834

St. dev residuals at range of 7-10 mm (GR,SWM,S3)

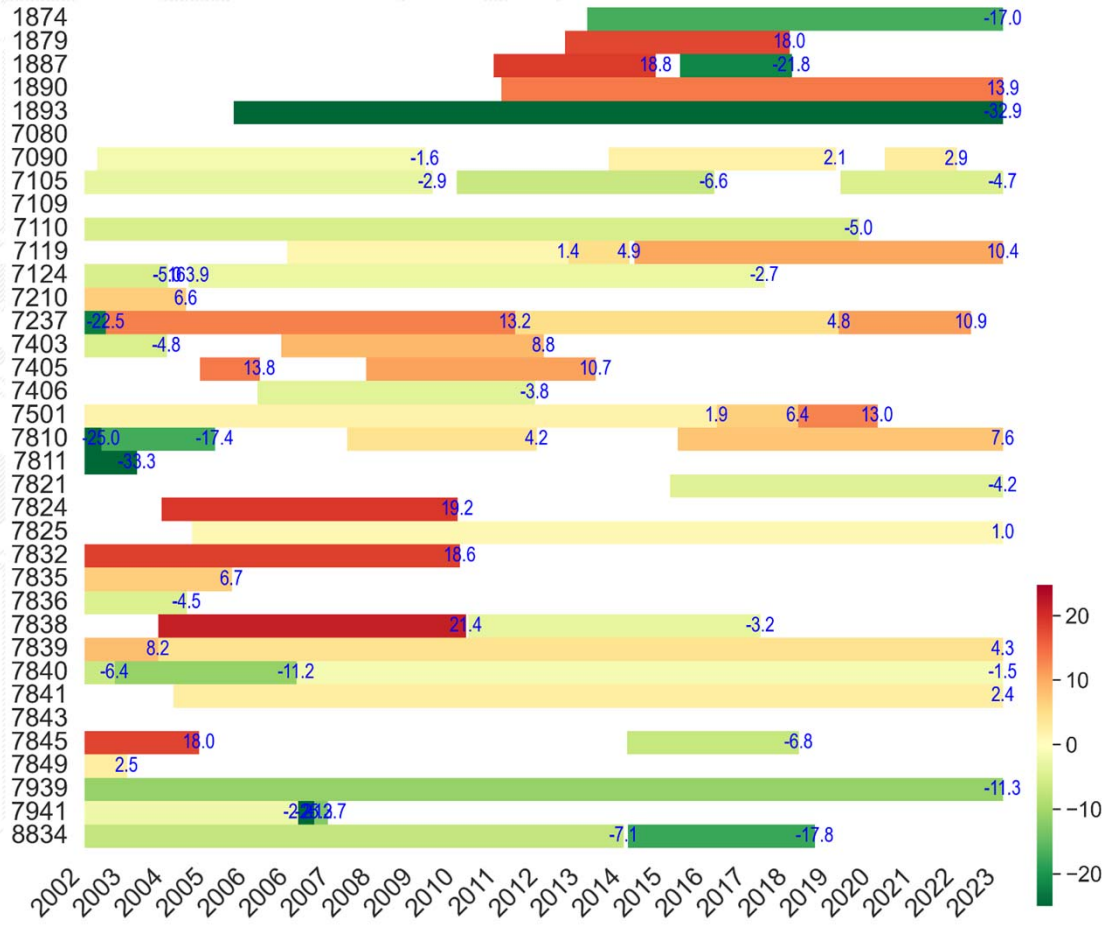
St. dev. reduced by 2-5 mm and no offset!
w.r.t the same group and (0)



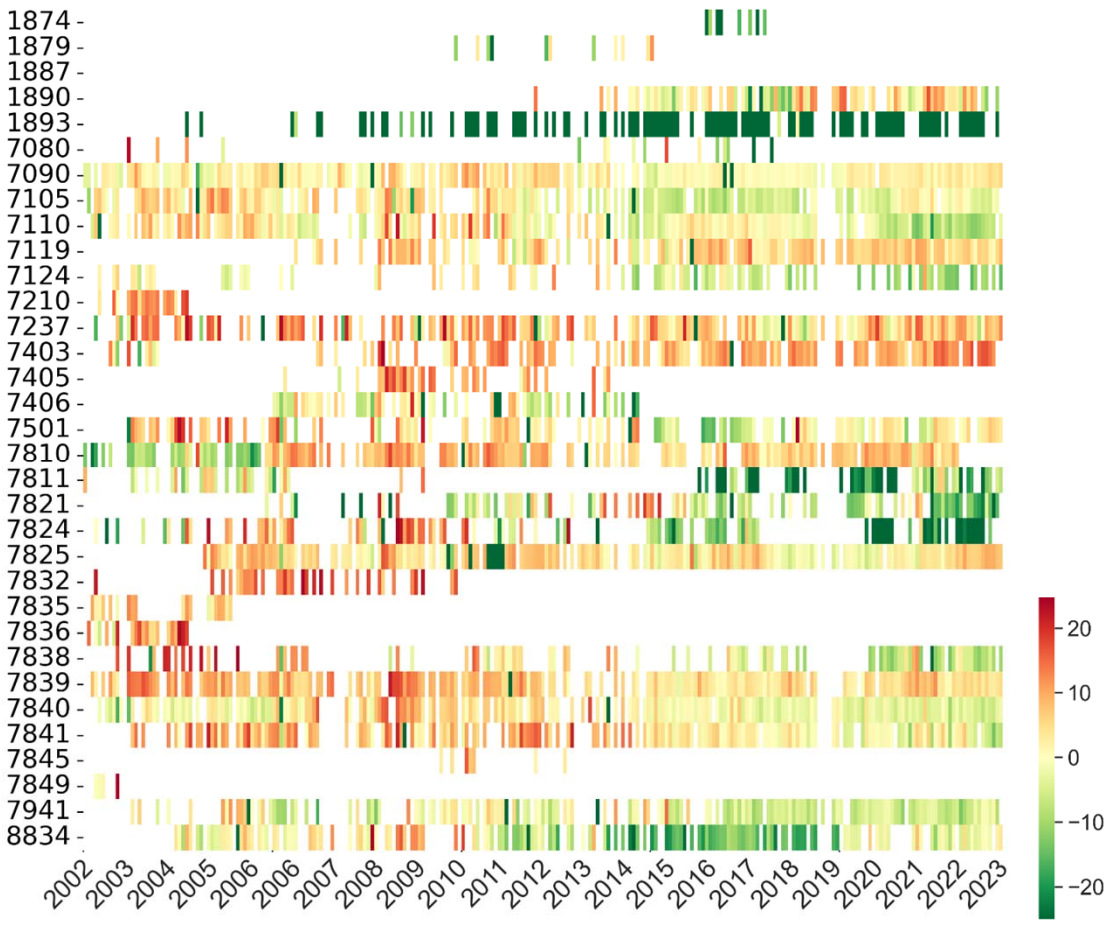
SLR residuals (mean+st.dev) [mm]

(3) a priori 30-day mean RB per station per 12LEOs group

Mean RBs LAG1 and LAG2 [mm]



30-day RBs station_LEOs [mm]



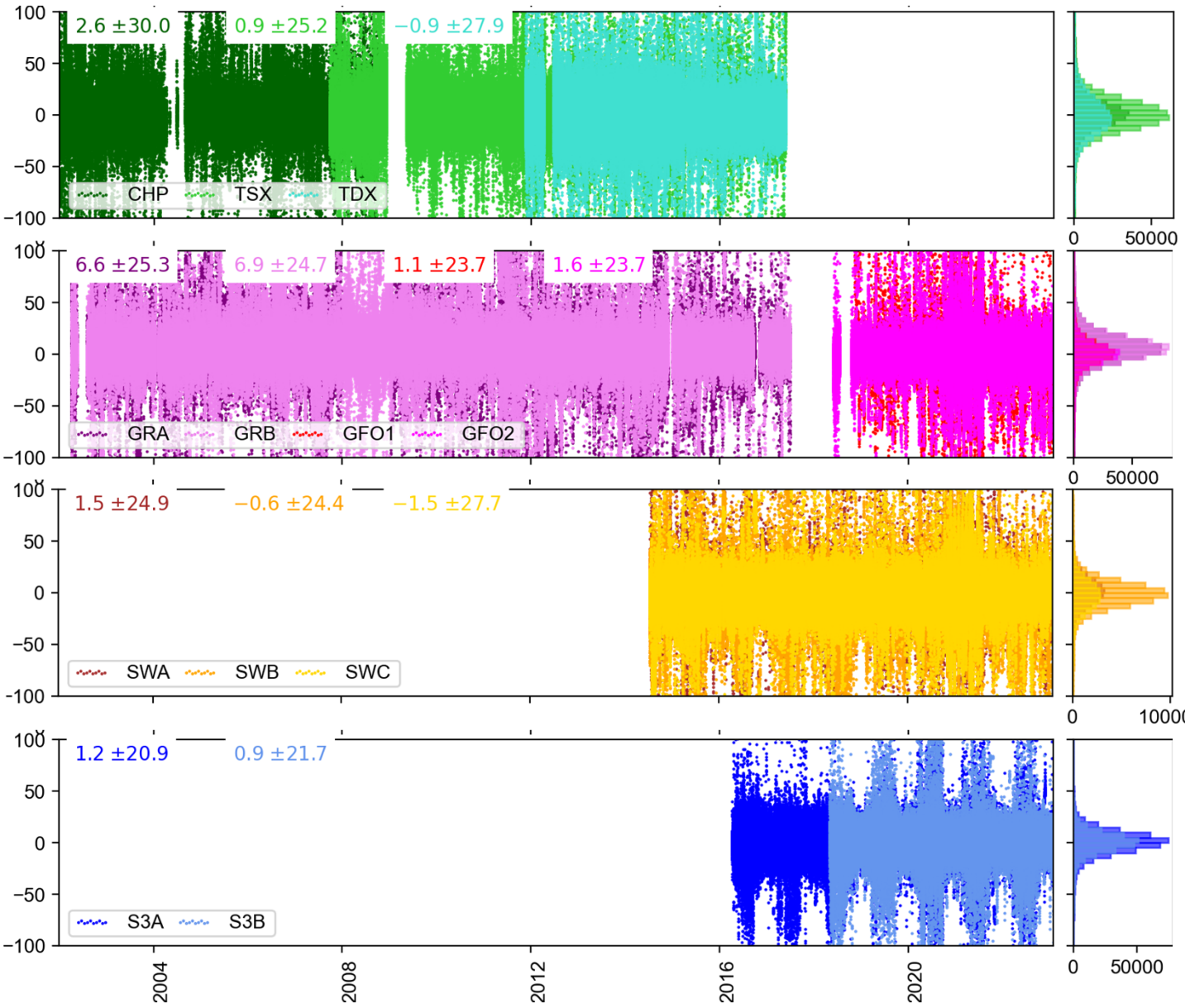
+MODEL/RANGE_BIAS section only

(3) a priori 30-day mean rbias per station per 12LEOs group

12 satellites, all stations

St. dev. increased by a few mm (~2-5mm)! w.r.t (0)

More sat. groups needed? To long period for RBs?



SLR residuals (mean+st.dev) [mm]

Summary and insights

(1) **Daily station-satellite RBs** reduce offsets, as well as st.dev. of SLR residuals by 2-7mm to the level of 7-10mm (GR, Swm, S3), but large no. of parameters

(2) **No need of a priori values.** A priori mean RB of LAG1/2 (DHF) + daily est. RB = daily est. RB. Identical effect on SLR validation

(3) 30-day mean RBs station-LEO or a priori mean RBs of LAG1/2 (DHF) are insufficient – decreased consistency between SLR and POD products

(4) **More tests:** retroreflector dependent groups / 7-day period / more LEOs

Same or different scheme for determination of parameters?

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Thank you for your attention!

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Many thanks to Filip Gałdyn (UPWr) for sharing his computing resources

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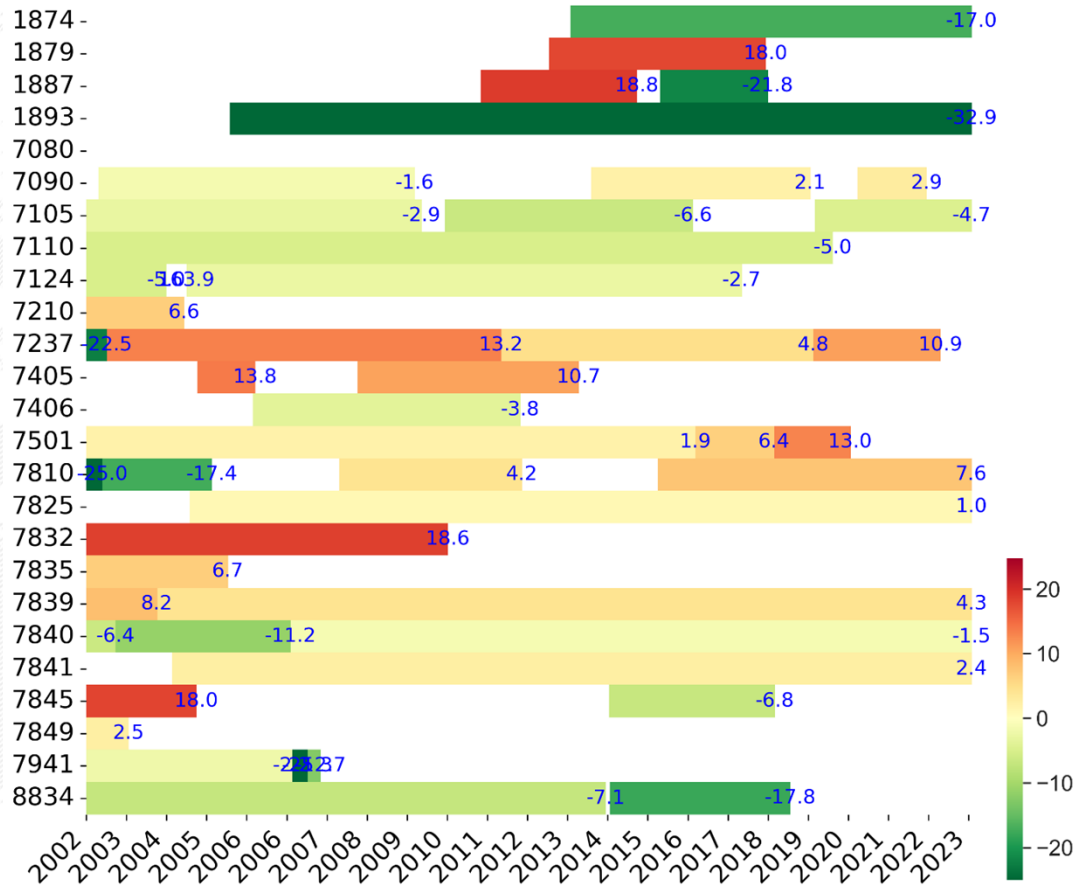
Future plans

1) **include more LEOs in the processing, e.g. Sentinel-6, Jason-1/2/3,**
   (calculations for Sentinels-3 – updated POD products from TUG)
2) **compare results with solutions based on other POD products, e.g. ESA**
3) **retroreflector dependent analysis on range corrections**
4) **extend period of analysis, resolving data gaps**

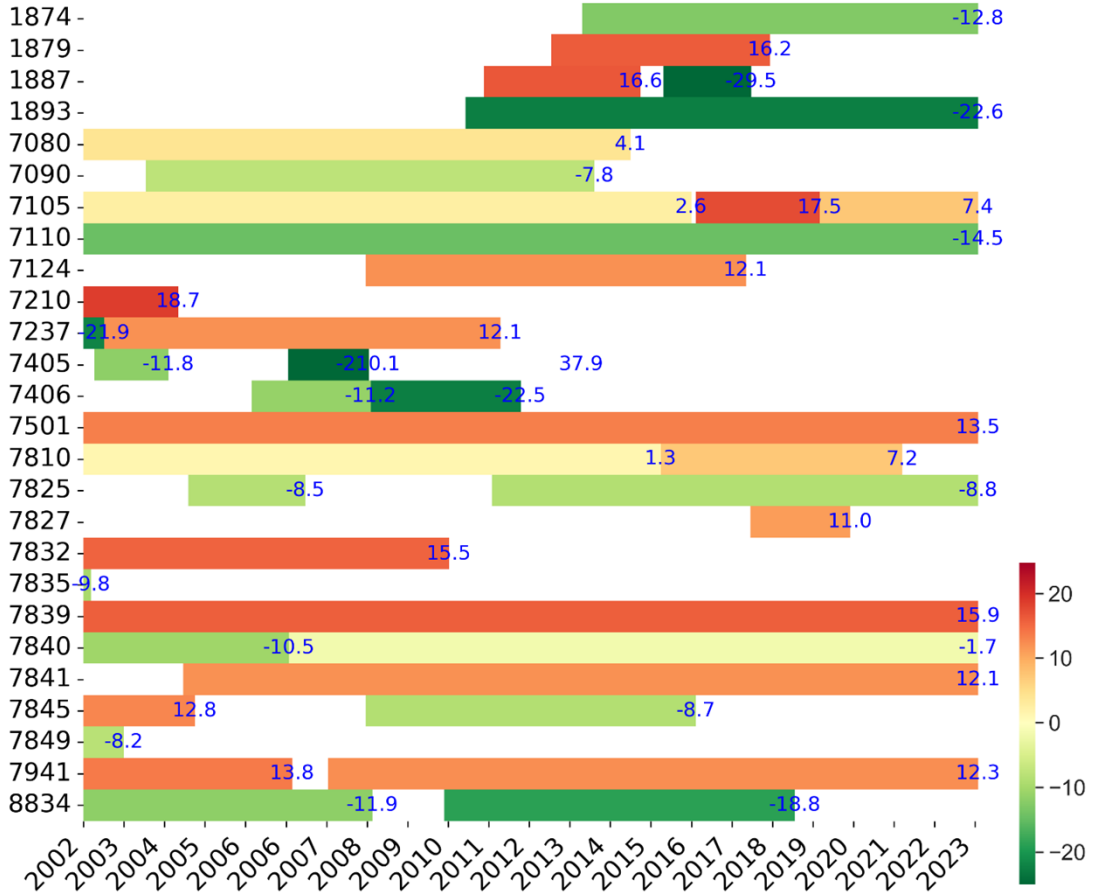
Range bias corrections from DHF240213

Mean range bias LAG1 and LAG2 [mm]



+MODEL/RANGE_BIAS section only

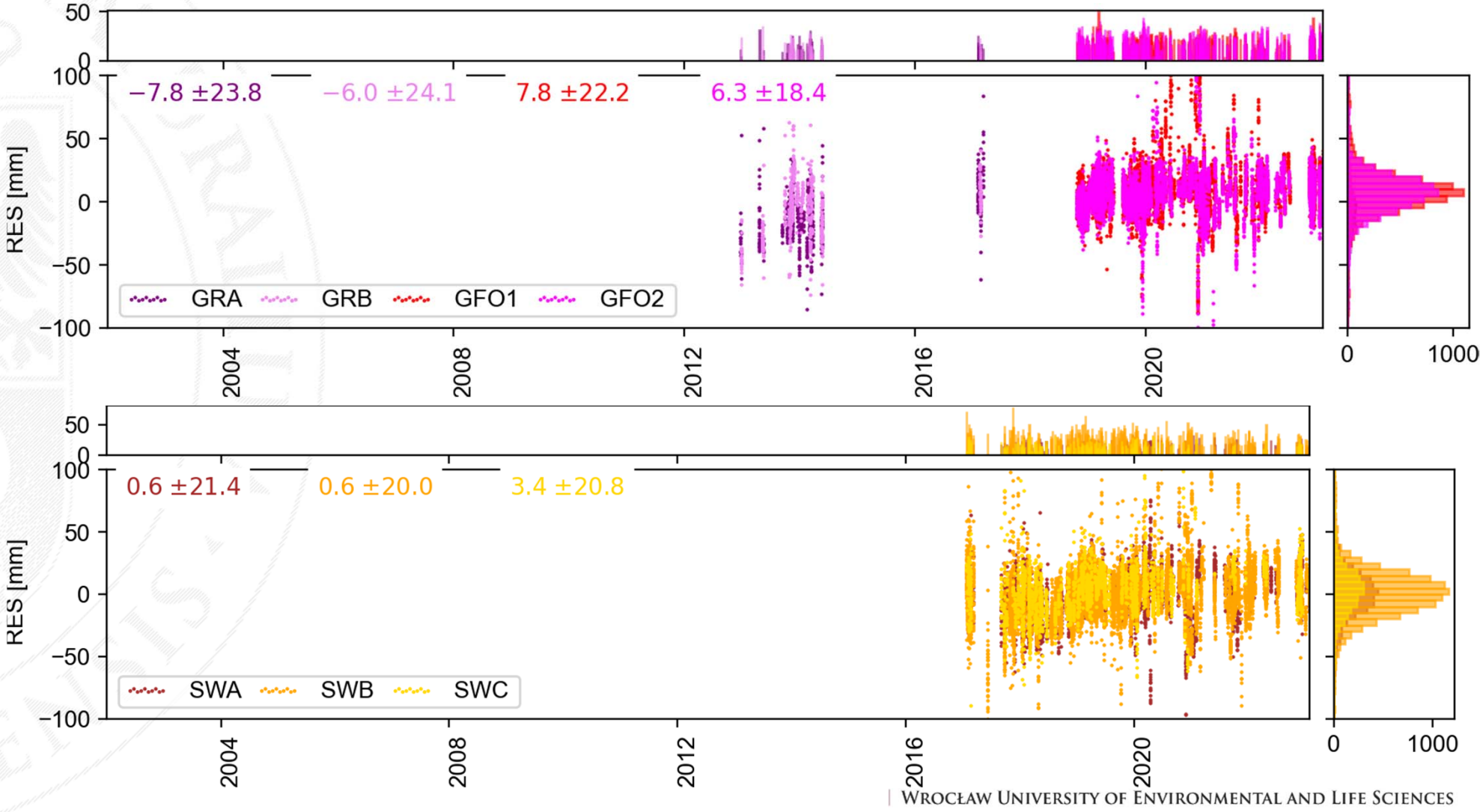
Mean range bias Eta1 and Eta2 [mm]



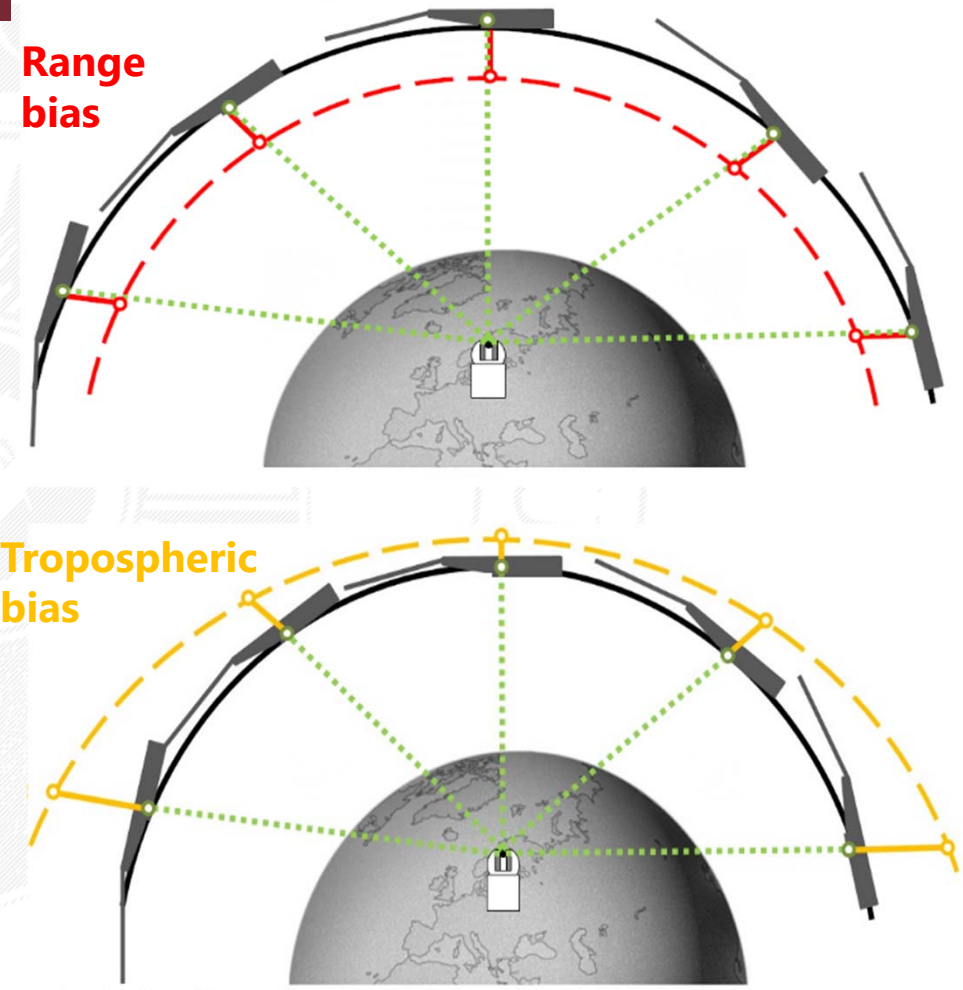
Yarragadee (7090),
Greenbelt (7105),
Haleakala (7119),
Hartebeesthoek (7501),
Zimmerwald (7810),
Graz (7839),
Herstmonceux (7840),
Potsdam (7841),
Matera (7941),
Wettzell (8834).
Wettzell (7827)
Mt Stromlo (7825)

Kunming (7819),(7820)

KUNMING station (7819, 7820)



Methods of reducing systematic effects in SLR residuals



- **Range biases** (constant corrections to modeled ranges):
  - from each satellite pass analysis to spherical satellites (Otsubo et al. 2019)
  - weekly station and station-satellite dependent to LAGEOS-1/2 (Appleby et al. 2016, Luceri et al.. 2019, Rodriguez et al. 2019)
  - 1-year station dependent to LEOs with station coordinate corrections (Arnold et al. 2019) / orbit offsets / time biases (Arnold et al. 2022)
  - 1-year station-satellite dependent to GNSS (Bury et al. 2021)
- **Troposphere delay** (zenith angle dependent corrections):
  - 10-day tropospheric biases for LAGEOS-1/2 (Drożdżewski et al. 2021)
  - tropospheric biases with N and E horizontal gradients (Drożdżewski et al. 2019)

- tropospheric bias (estimated using partial derivatives of the dry part of the Global Mapping Function, Böhm et al. 2006)

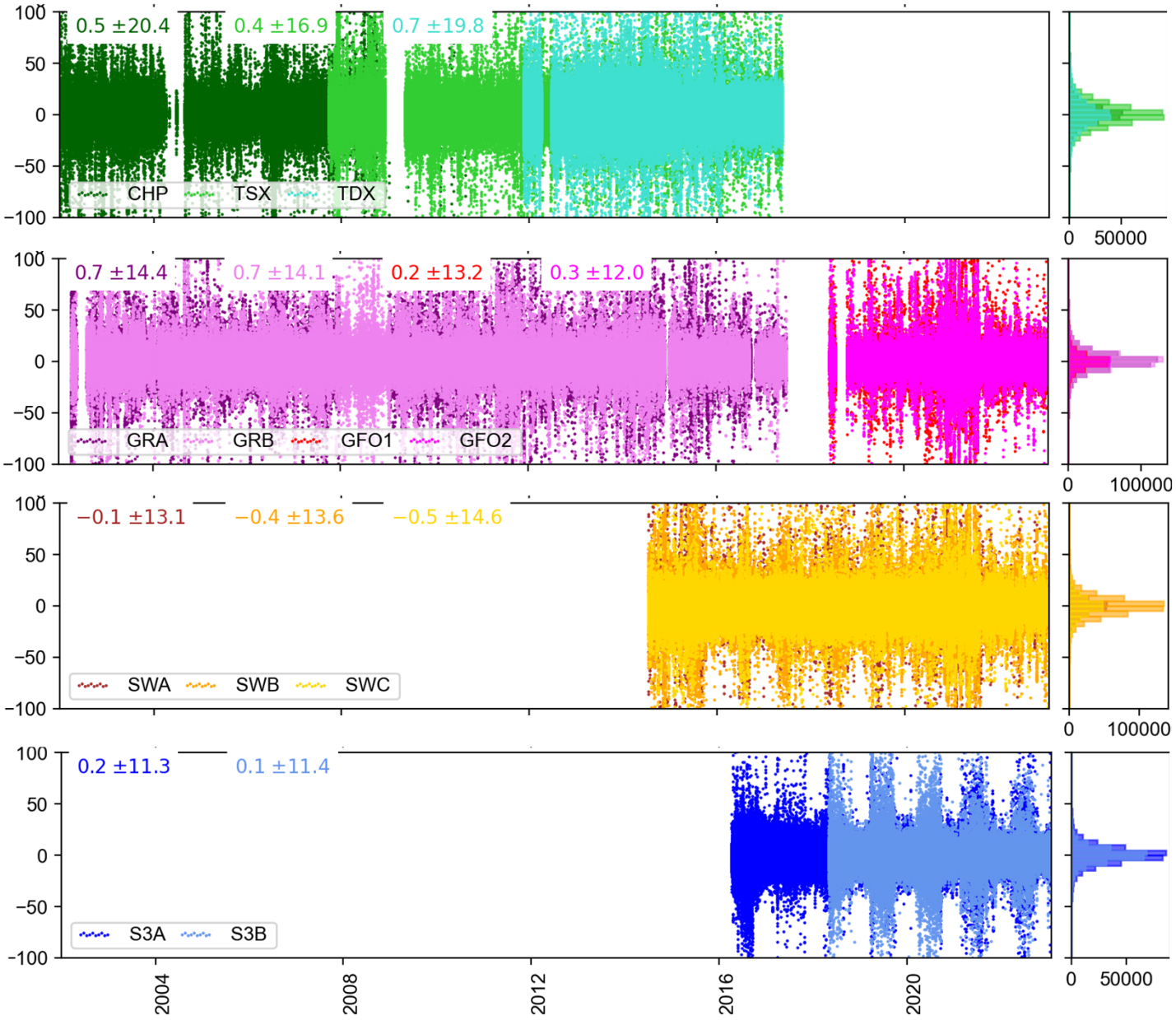
Absolute maximum of the residuals	0.15	m
Maximum overall sigma	20.0	mm
Multiplication factor for overall sigma	2.5	

(4) troposphere bias (zenit correction)

12 satellites, all stations

St. dev residuals at range of 10-19mm

St. dev. reduced by 2-7 mm and no offset!
w.r.t (0)



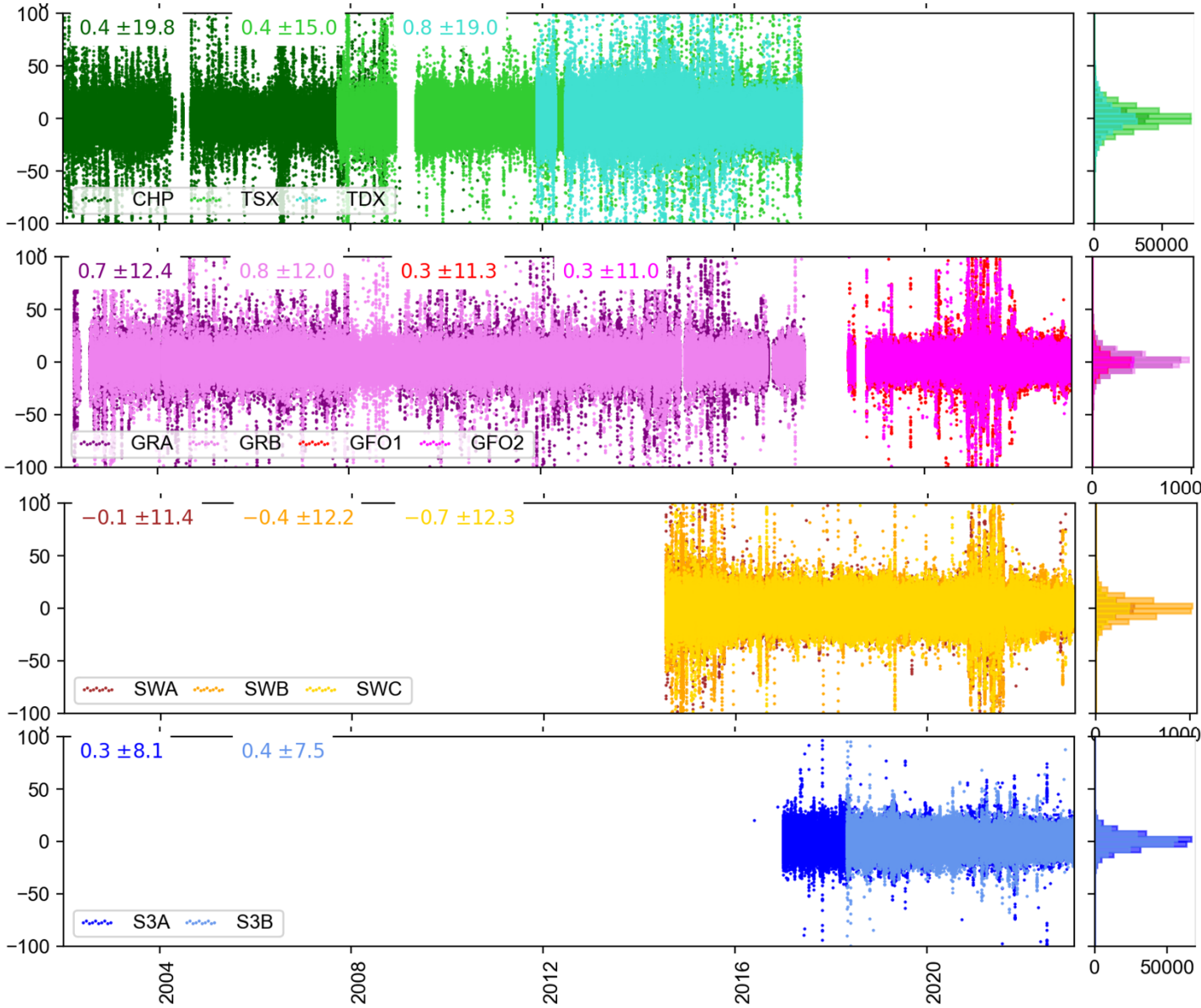
SLR residuals (mean+st.dev) [mm]

(4) troposphere bias (up correction)

12 satellites, high-performing stations (12):
7090, 7105, 7501, 7810, 7825, 7827, 7839, 7840, 7841, 7941, 7119, 8834

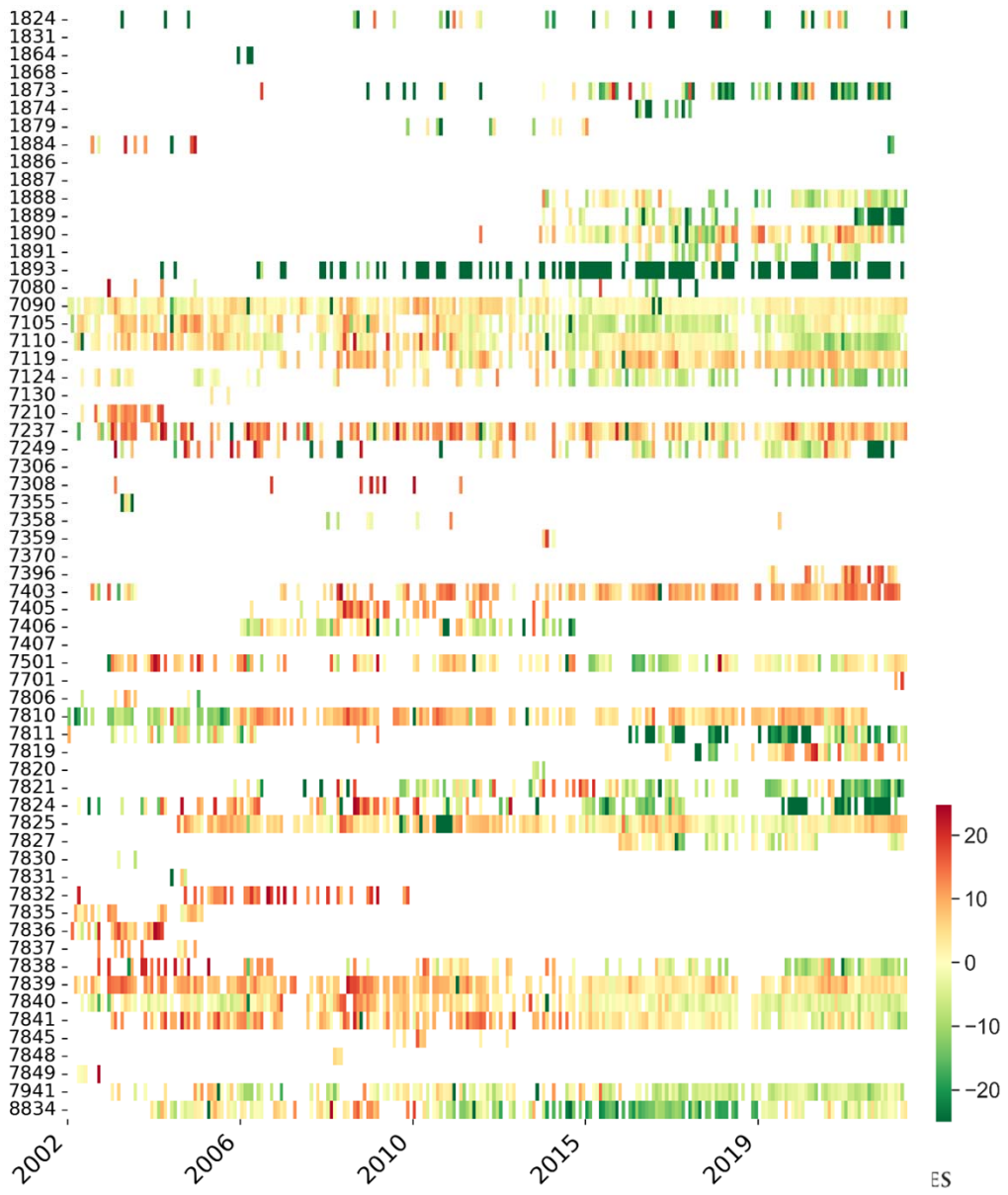
St. dev residuals at range of 7-10 mm

St. dev. reduced by 2-5 mm and no offset!
w.r.t the same group and (0)



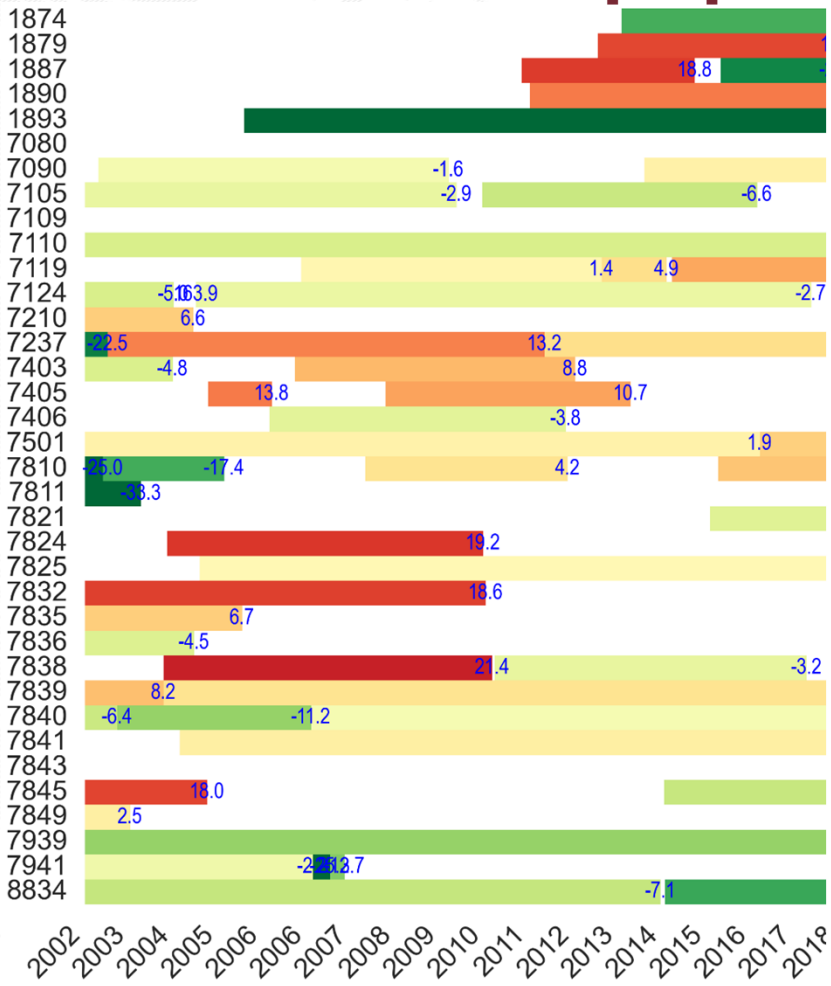
SLR residuals (mean+st.dev) [mm]

Range bias corrections from 30 day mean

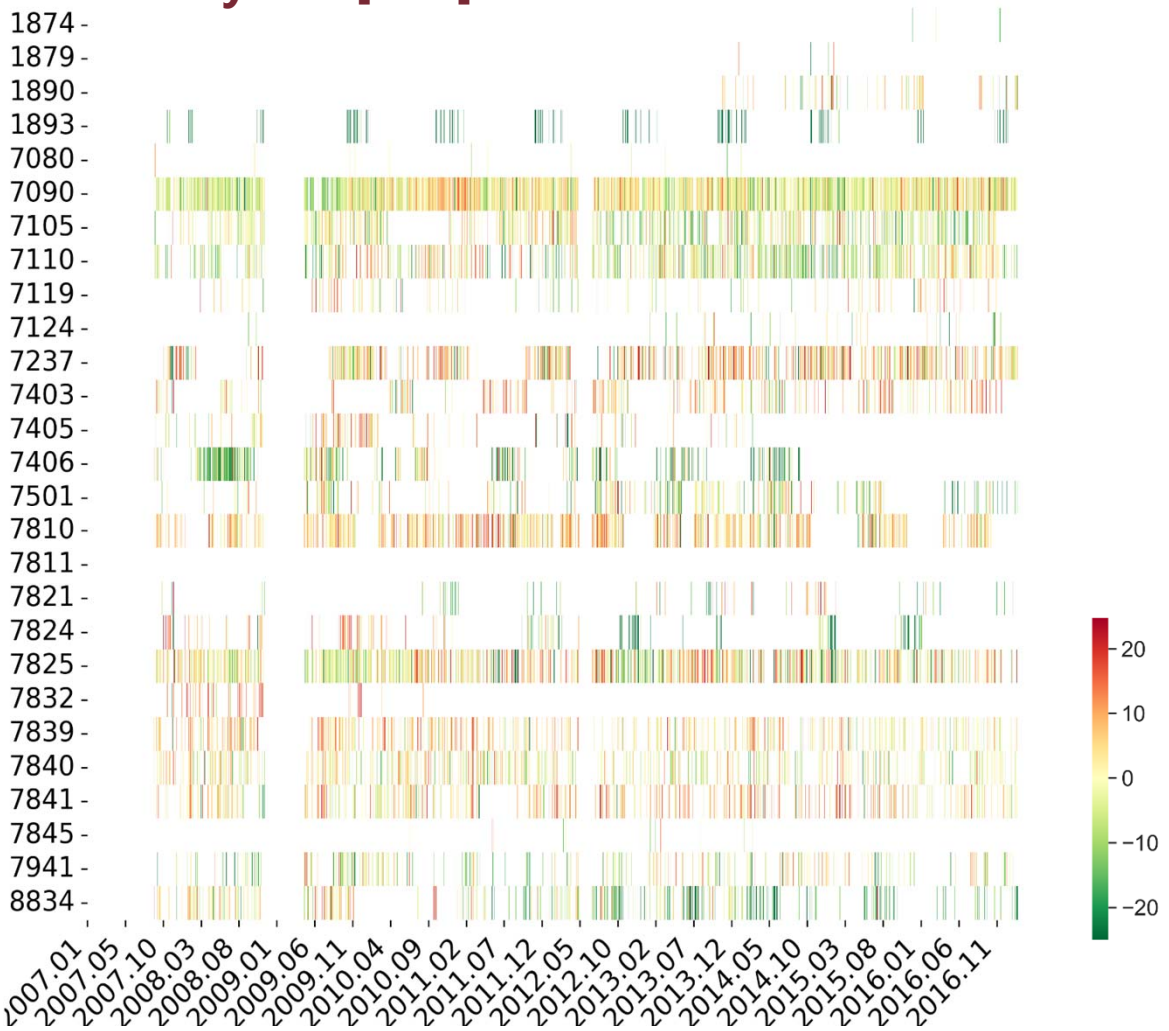


(2) a priori mean RB from LAG1/2 (DHF)+est. daily RB = est. daily RB

Mean RBs LAG1 and LAG2 [mm]

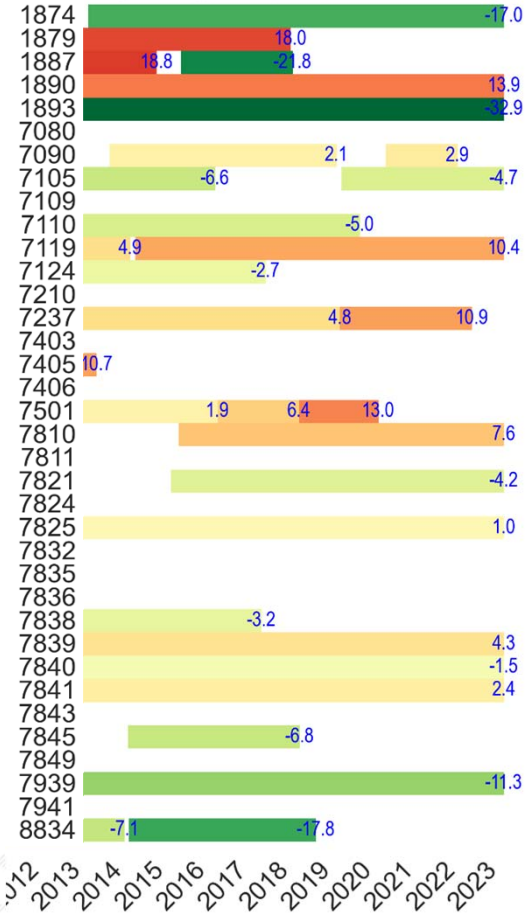


TSX daily RBs [mm]



(2) a priori mean RB from LAG1/2 (DHF)+est. daily RB = est. daily RB

Mean RBs LAG1 and LAG2 [mm]



SWARM-B daily RBs [mm]