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SLR validation of the IGS Repro3 orbits for ITRF2020

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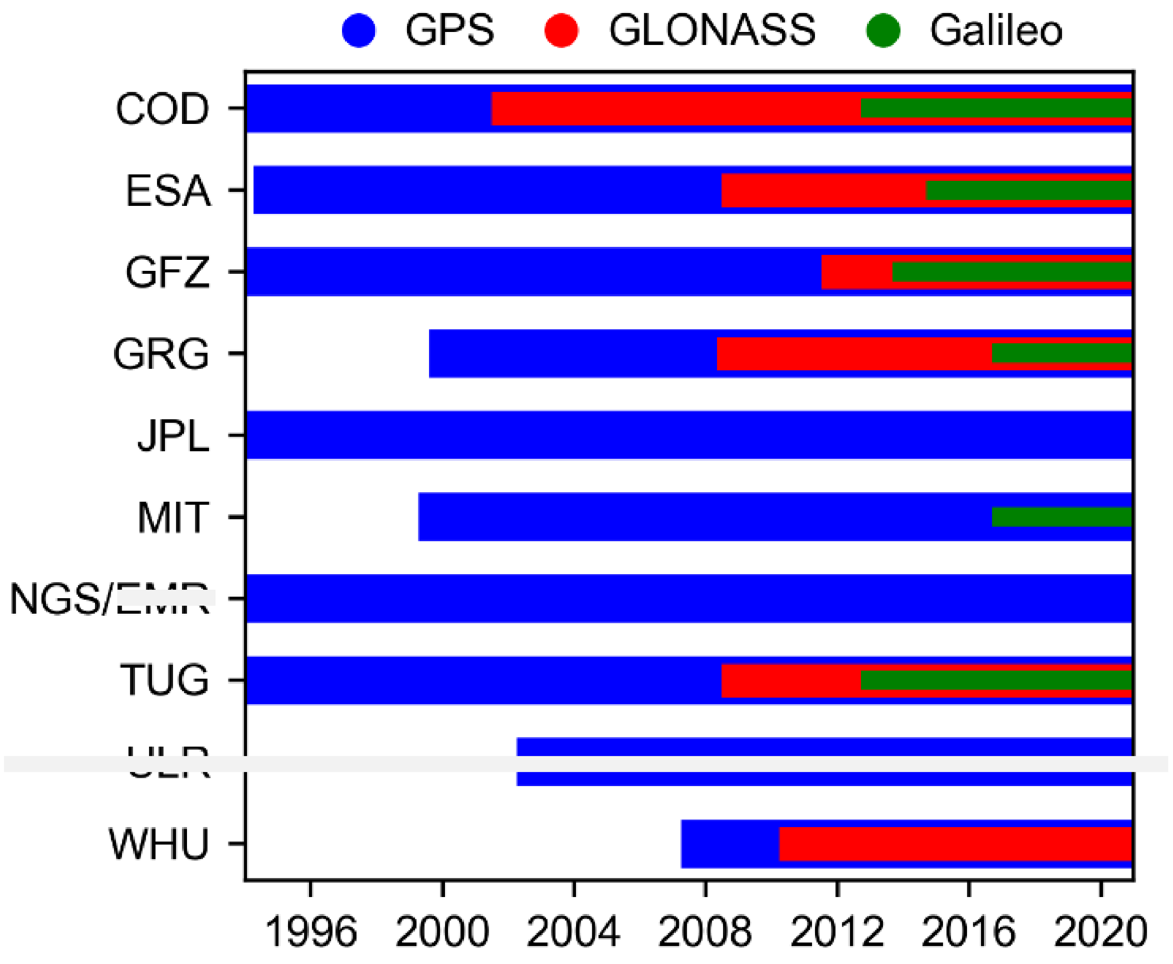
IGS Repro3 orbit contributions

- The Repro3 products provided the IGS contribution to the International Terrestrial Reference Frame 2020.
- In total, eleven IGS Analysis Centers contributed to the IGS Repro3 initiative by providing their products.
- ULR and EMR did not provide orbit products.
- **Reprocessing products should follow the latest models and methodology standards** drawn from the long-term experience and recommendations of the scientific community.
- The main findings and guidelines concerning the IGS Repro3 processing standards were put together during the IGS Analysis Center Workshop 2019 in Potsdam (Germany). e.g.: Solar radiation pressure, HF-EOP…



ITRF2020 – IGS contribution

DD – double differences; ZD – zero differences;

IF – Iono-free linear combination;

	COD	ESA	GFZ	GRG	JPL	MIT	TUG	WHU
GNSS	GPS (1994/01/02) GLO (2002/01/01) GAL (2013/01/01)	GPS (1995/01/01) GLO (2009/01/01) GAL (2015/01/01)	GPS (1994/01/02) GLO (2012/01/01) GAL (2013/12/21)	GPS (2000/05/03) GLO (2008/11/04) GAL (2016/12/31)	GPS (1994/01/02)	GPS (2000-01-02) GAL (2017-01-01)	GPS (1994/01/01) GLO (2009/01/01) GAL (2013/01/01)	GPS (2008-01-01) GLO (2010-09-28)
Arc	72h	24h	24h	24h	30h	24h + connceted SRP	24h	24h
Observable types	IF DD	IF ZD	IF ZD	IF ZD	IF ZD	IF DD	RAW (Strasser et al. 2019)	IF DD
A priori solar radiation pressure	Box-wing (Galileo)	Box-wing	-	Box-wing	GSPM13b (Sakumura et al 2017); GPS Block III: Manufacturer Table	Direct only	Box-wing	-
Empirical parameters	(7 par) D0, Y0, B0, B1C, B1S, D2C, D2S (Arnold et al. 2015) for Galileo eclipses (when |β|<12), additional parameters are estimated: D1C, D1S and Y0 (FOC only) (Sidorov et al. 2020)	(7 par) D0, Y0, B0, + B1C, B1S + Along-track 1C/1S	(9 par) D0, Y0, B0, B1C, B1S, D2C, D2S, D4C, D4S	(8 par) Y0, B0, B1C, B1S, D2C, D2S, D4C, D4S	Solar Scale and Y-Bias	(9 par - satellite/week dependent) D0, Y0, B0, B1C, B1S, D2C, D2S, D4C, D4S	(7 par) D0, Y0, B0, B1C, B1S, D2C, D2S	(7 par) D0, Y0, B0, B1C, B1S, D2C, D2S
Stochastic parameters	in radial along-track and cross-track at orbit midnight (Dach et al. 2021)	-	in radial along-track and cross-track at noon	in radial along and cross-track in eclipse	-	-	in radial along-track and cross-track at noon	-

- Most of the ACs **use either undifferenced (ESA, GFZ, GRG, JPL) or double-differenced (COD, MIT) ionospheric-free linear combinations (L3) of two selected frequencies**. **TUG is the only AC that uses raw (undifferenced and uncombined) observables from all available signal frequencies** (Strasser et al. 2019).

- The orbital arc is **typically 24 hours**, but **COD favors a long-arc solution over three days**, whereas JPL process 30 hours to obtain 6 hours of overlaps surrounding the day (3 hours on each side).

- **COD (for Galileo only), ESA, GRG, and TUG use the box-wing model as the a priori SRP model. MIT uses the a priori SRP model to compute only the constant direct radiation pressure acting on the satellites (D0).** The **JPL products rely on the GSPM13b model** (Sakamura et al. 2017), which is supported by additionally estimated solar scale and Y-bias coefficients.

- **All the ACs estimate the empirical parameters; however, different sets** of these coefficients are determined by different ACs, e.g., ECOM or radial/along track.

- **Some ACs fit stochastic parameters to handle orbit modeling deficiencies**. GRG, TUG and GFZ estimate additional stochastic **parameters every noon in radial, along-track and cross-track directions**. It should be noted that GRG, unlike TUG and GFZ, estimates stochastic parameters **only in satellite eclipses**. For Repro3 products, COD developed a novel approach to estimating pseudo-stochastic parameters in orbit midnight.

IGS ACC orbit combination by Geoscience Australia (GA)

Orbit combination by IGS ACC (GA)

- Upgrade of the legacy software
- Satelite-specific weighting

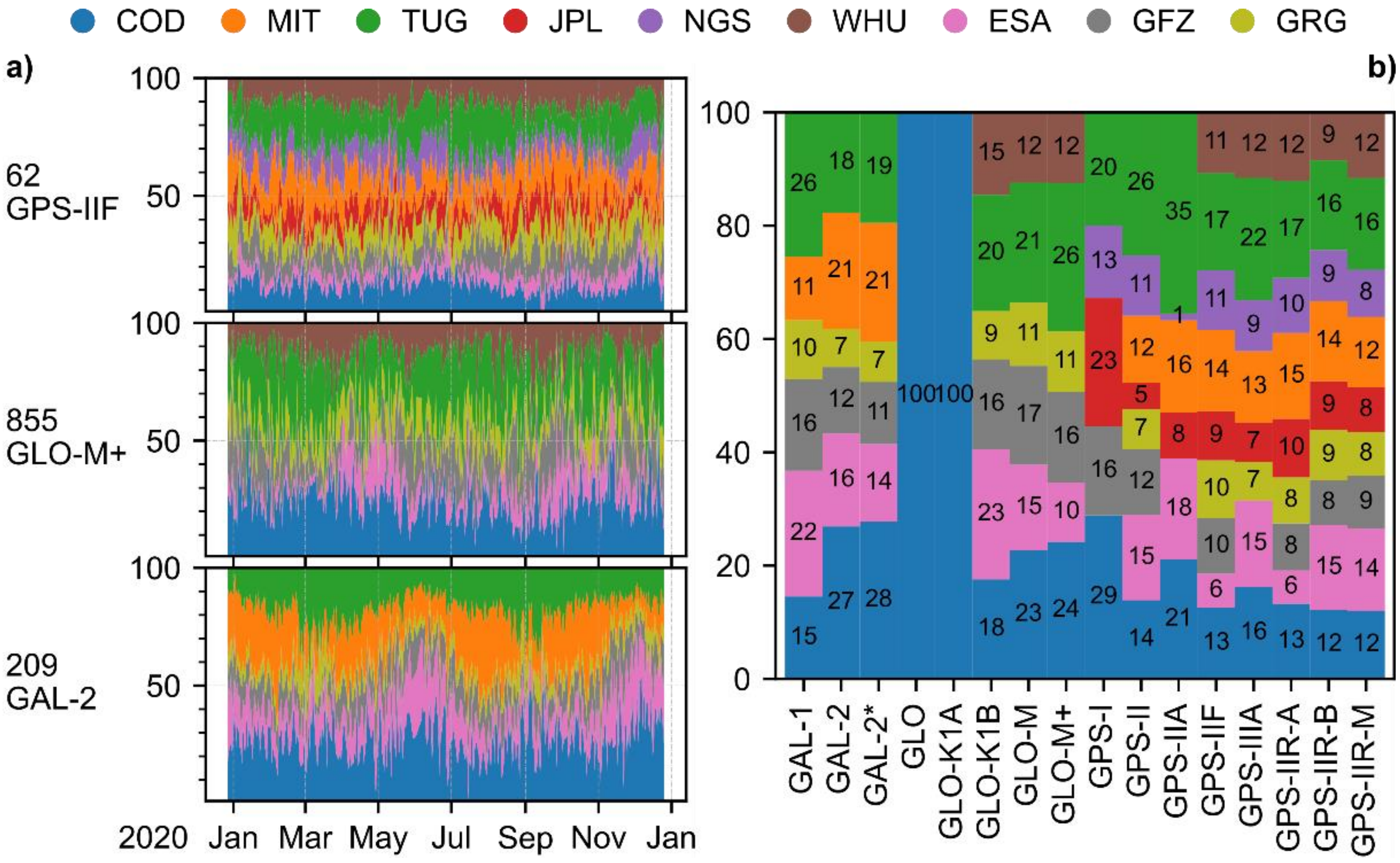
Internal consistency:

- In 2020, the mean consistency of the combination is at the level of **9, 23, and 15 mm** for **GPS, GLO, and GAL,** respectively.

Weights of the individual ACs:

- GPS: each of the nine ACs contributes with a weight of several percentages
- GLO-M: COD (23%) and TUG (21%)
- GLO-K1B: ESA (23%) and TUG (20%)
- GAL-FOC: COD (27%) and MIT (21%)
- GAL-IOV: TUG (26%) and ESA (22%)

Time series of weights of individual ACs in the combined orbit product for specific satellites representing different satellite types (a) and mean weights for different satellite types in the last year of available products (b) in %.



SLR validation of IGS Repro3 products

Mean offset of SLR residuals [mm]

	COD	ESA	GFZ	GRG	IGS	MIT	TUG	WHU
GAL-FOC	6.2	1.8	-6.9	35.3	13.3	15.2	29.8	
GAL-FOCe	8.1	2.1	-1.2	28.0	15.0	20.0	25.6	
GAL-IOV	-3.4	0.6	-10.2	14.0	-2.6	-0.1	-7.6	
GLO-K1B	3.2	14.0	24.1	10.8	13.9		11.6	21.6
GLO-M	-1.5	-1.3	-2.8	5.4	-1.1		-5.3	-0.3
GLO-M+	37.2	37.6	33.7	45.1	37.1		33.3	37.3

GAL FOC: vary from -7 to 35 mm.
GAL IOV: vary from -10 to 14 mm
GLO-M: single mm
GLO-K1B: vary from 3 to 24 mm

- The mean offset in SLR residuals varies between individual ACs **by up to 4 cm for Galileo-FOC.**
- The differences in the offsets of SLR residuals are consistent with Sakic et al. (2022)
- Dach and Springer (2022) indicated the differences between the Galileo FOC orbits reaching up to ±30 mm, depending on the AC.
- Reason: Different antena thrust; orbit modeling?
- Bearing in mind the potential contribution of the GNSS-based scale to the next releases of the ITRF, **it is essential to maintain the inter-AC scale consistency.**
- The mean offsets of the GLO-M and GAL-IOV are consistent at the level of single mm between the individual ACs.

SLR validation of IGS Repro3 products

- **ESA orbit products deliver the most accurate products for most of the satellite groups:** GAL FOC/FOCe/IOV, GLO-M.
- TUG products are almost equal to ESA in terms of standard deviation of SLR residuals for Galileo-FOC.
- **COD, TUG and ESA delivers the best GLONASS-K1B orbits.**
- **The IGS combined orbits are never worse than 10% compared to the best individual solution.**

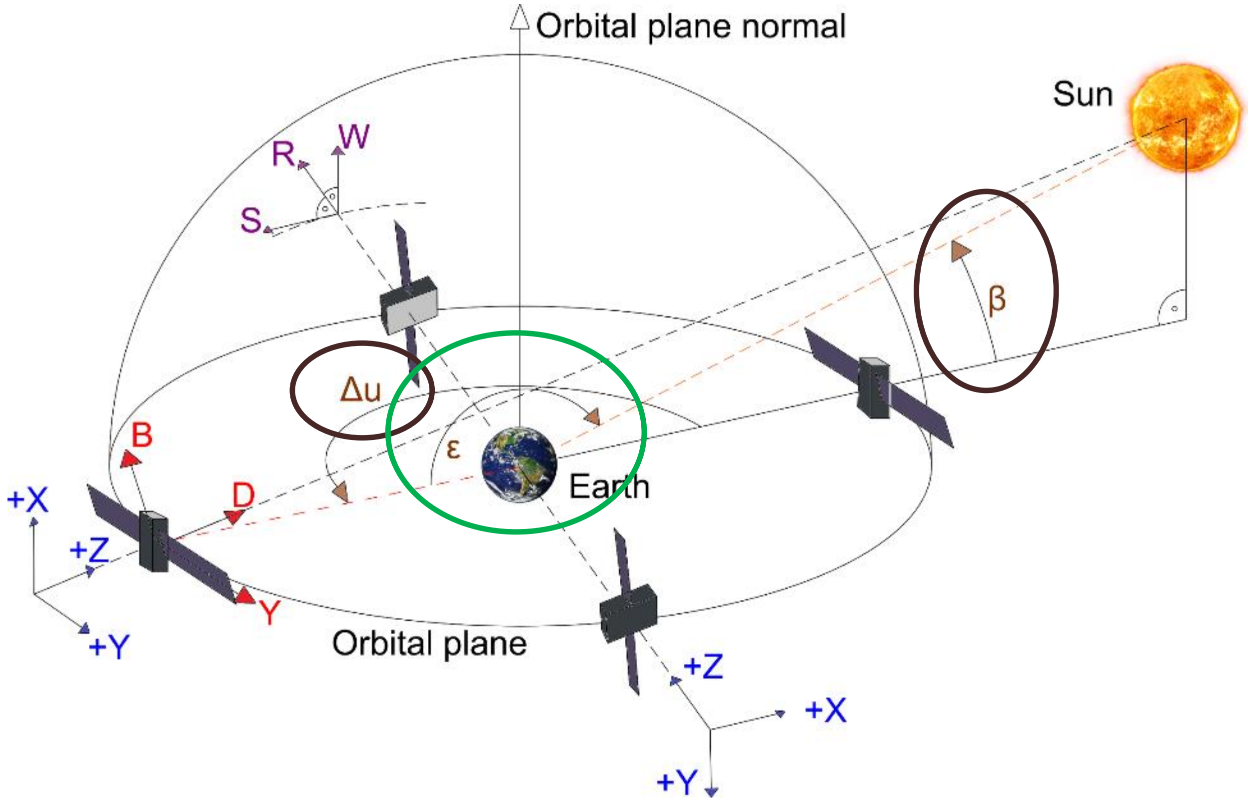
Standard dev. of SLR residuals [mm]

	COD	ESA	GFZ	GRG	IGS	MIT	TUG	WHU
GAL-FOC	17.9	13.2	23.0	15.8	13.7	17.7	13.6	
GAL-FOCe	17.6	14.1	17.6	16.6	13.4	16.6	14.7	
GAL-IOV	20.8	15.3	22.9	28.8	16.3	20.2	18.4	
GLO-K1B	17.8	18.5	21.4	20.7	17.2		17.0	26.4
GLO-M	22.1	19.1	27.9	23.9	20.3		23.1	28.5
GLO-M+	17.0	14.6	21.9	21.1	15.2		18.1	23.2

GAL FOC: 13 mm (ESA) 14 mm (IGS)
GAL FOCe: 14 mm (ESA) 13 mm (IGS)
GAL IOV: 15 mm (ESA) 16 mm (IGS)
GLO-M: 19 mm (ESA) 20 mm (IGS)
GLO-K1B: 17 mm (TUG) 17 mm (IGS)

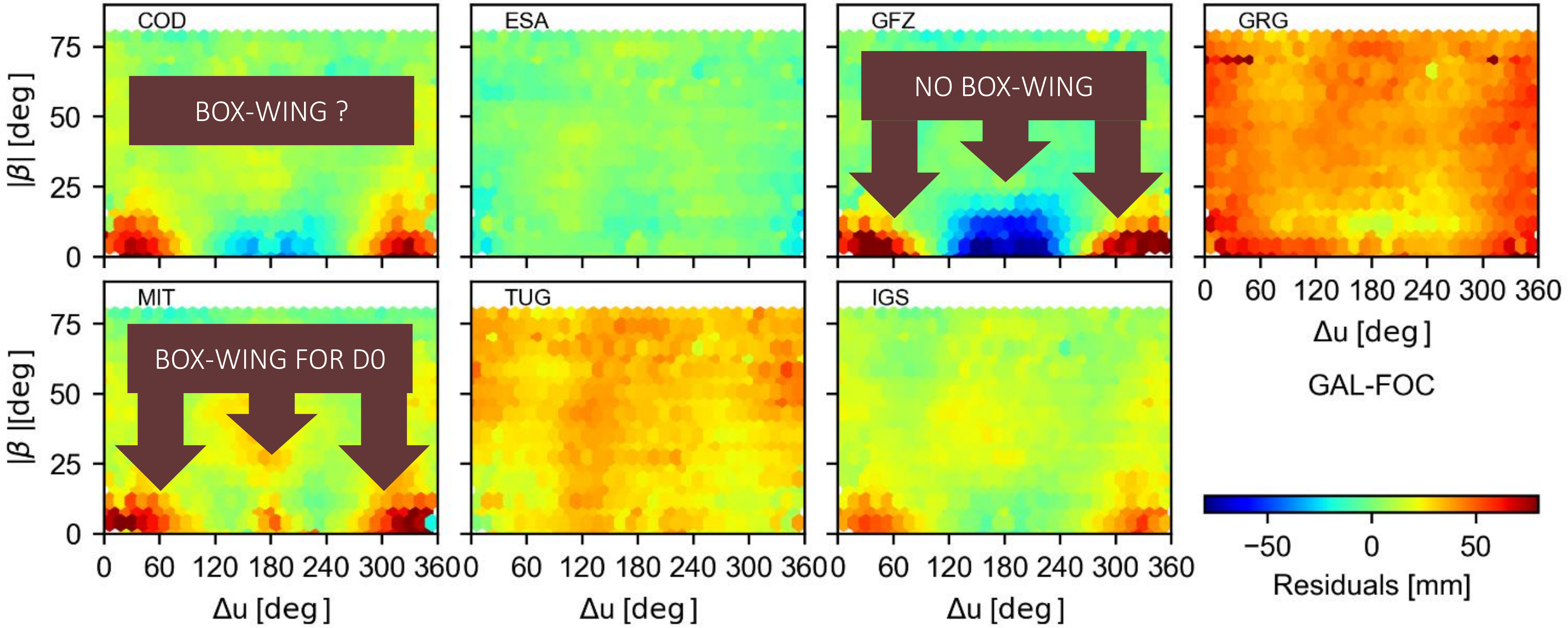
SLR validation of GNSS orbits

- Searching for patterns in SLR residuals in different satellite-Sun-Earth geometry
  - SLR residuals as a function of β and argument of latitude of the satellite with respect to the argument of the latitude of the Sun (Δu),
  - SLR residuals as a function of elongation angle (ε)

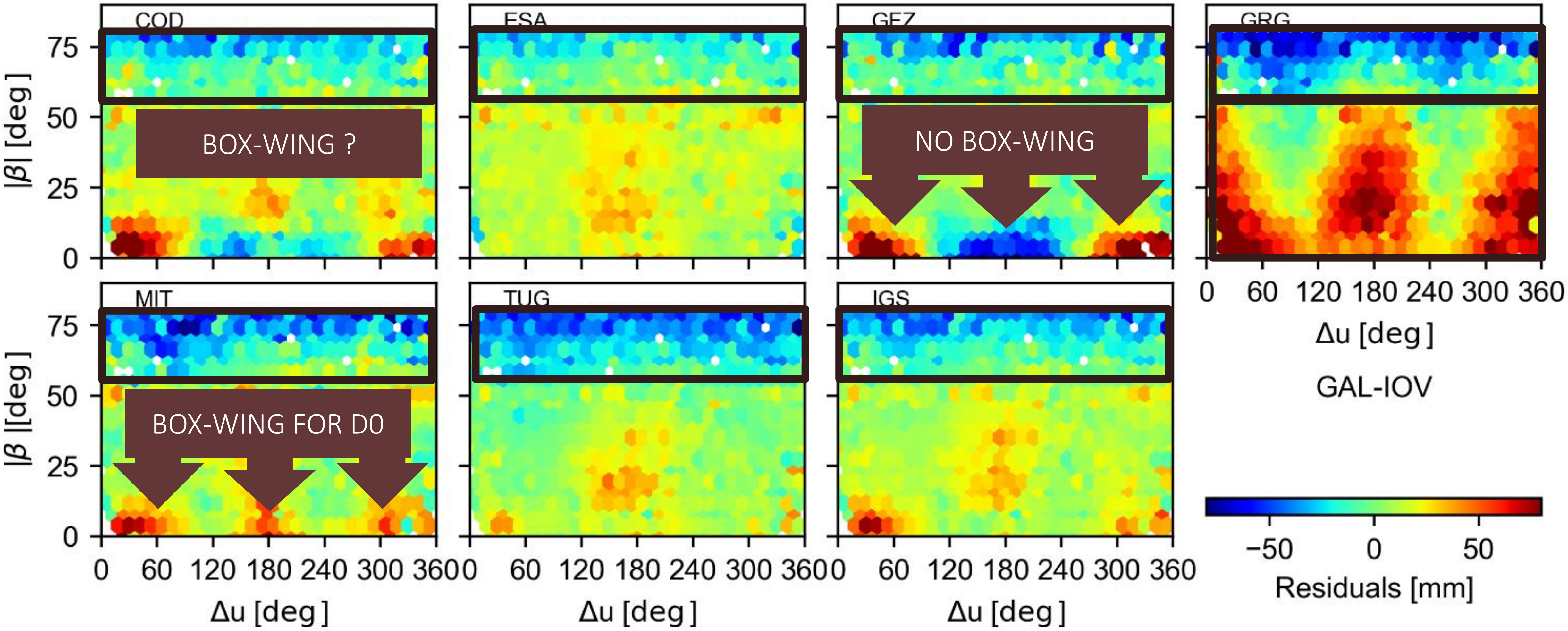


satellite-Sun-Earth geometry

Orbit modeling issues - searching for patterns in SLR residuals (GALILEO FOC)

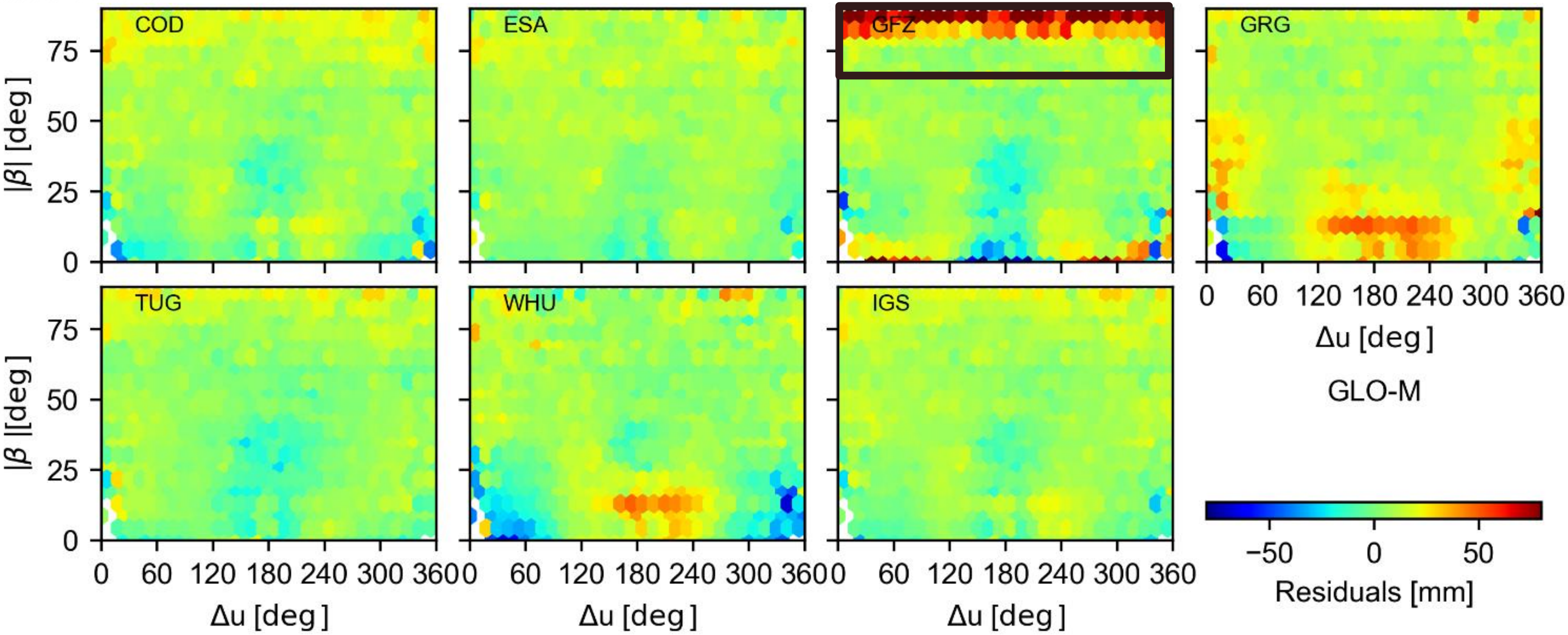


Orbit modeling issues - searching for patterns in SLR residuals (GALILEO IOV)

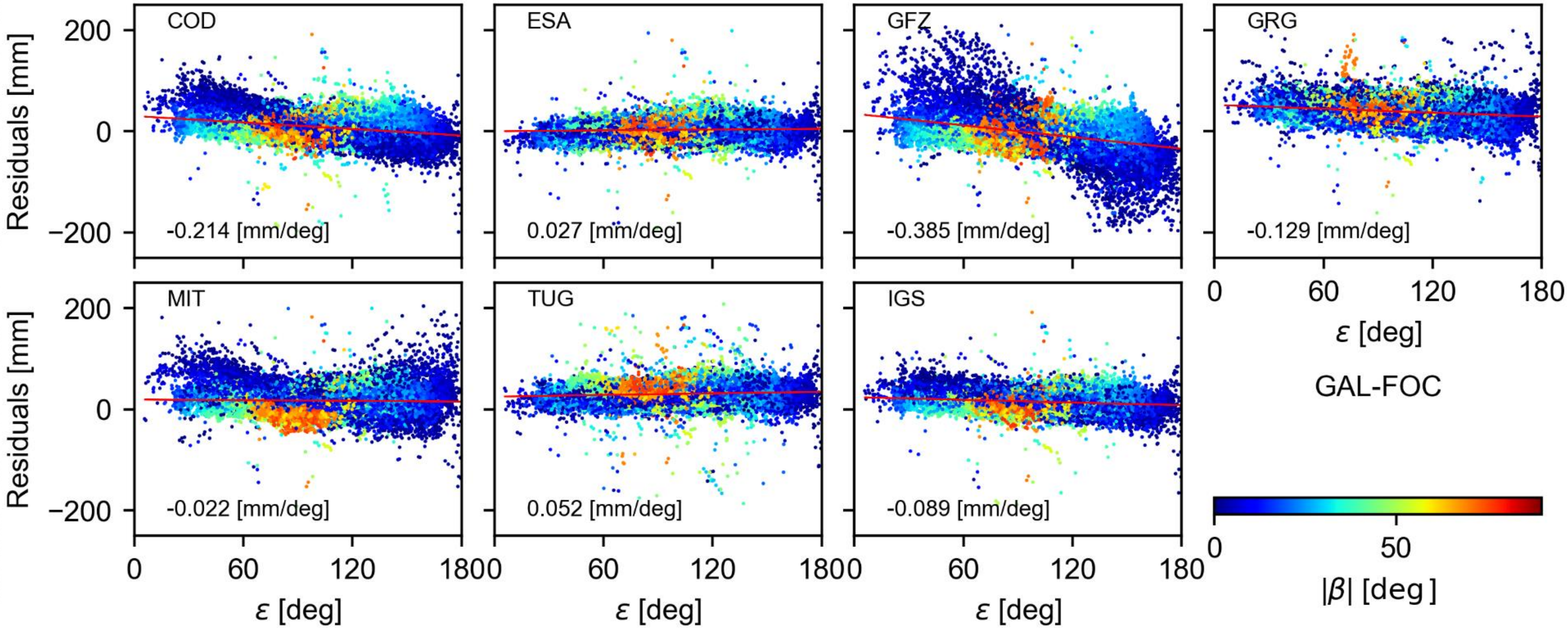


- Only Galileo-IOV 103 (Plane-C) affected because of higher β than the other orbital planes

Orbit modeling issues - searching for patterns in SLR residuals (GLONASS-M)



Orbit modeling issues - searching for patterns in SLR residuals (GALILEO FOC)



Conclusions

- Analysis of SLR residuals indicates some issues in the orbit modeling for the individual types of the GNSS Satellites. Some of these issues have been already mitigated by IGS ACs (ESA, TUG);

- There is a slight discrepancy between the weights of individual ACs in the combination and the quality of the individual AC products, as assessed externally by SLR.

- Taking the Galileo-FOC satellites as an example, **COD delivered 50% of the solutions with the greatest weight, swapping with MIT and TUG in approximately 25% and 15% of the remaining epochs, respectively**. On the other hand, the **SLR analysis revealed that the ESA product was the most accurate in terms of orbit modeling**, as measured by the number of artificial signatures in SLR residuals decomposed in different Sun-Earth-satellite geometries.

- The weights of the individual products in the combination are determined based on the consistency of the individual product with the mean model, i.e., the the better consistency, the higher the weight of the contribution in the combination. Unfortunately, any combination software is currently blind to the systematic effects, such as patterns in SLR residuals → **Feedback for the new IGS Combination Task Force**

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Thank you for your attention

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Special thanks to all the IGS Repro3 contributors for developing and distributing their orbit products!

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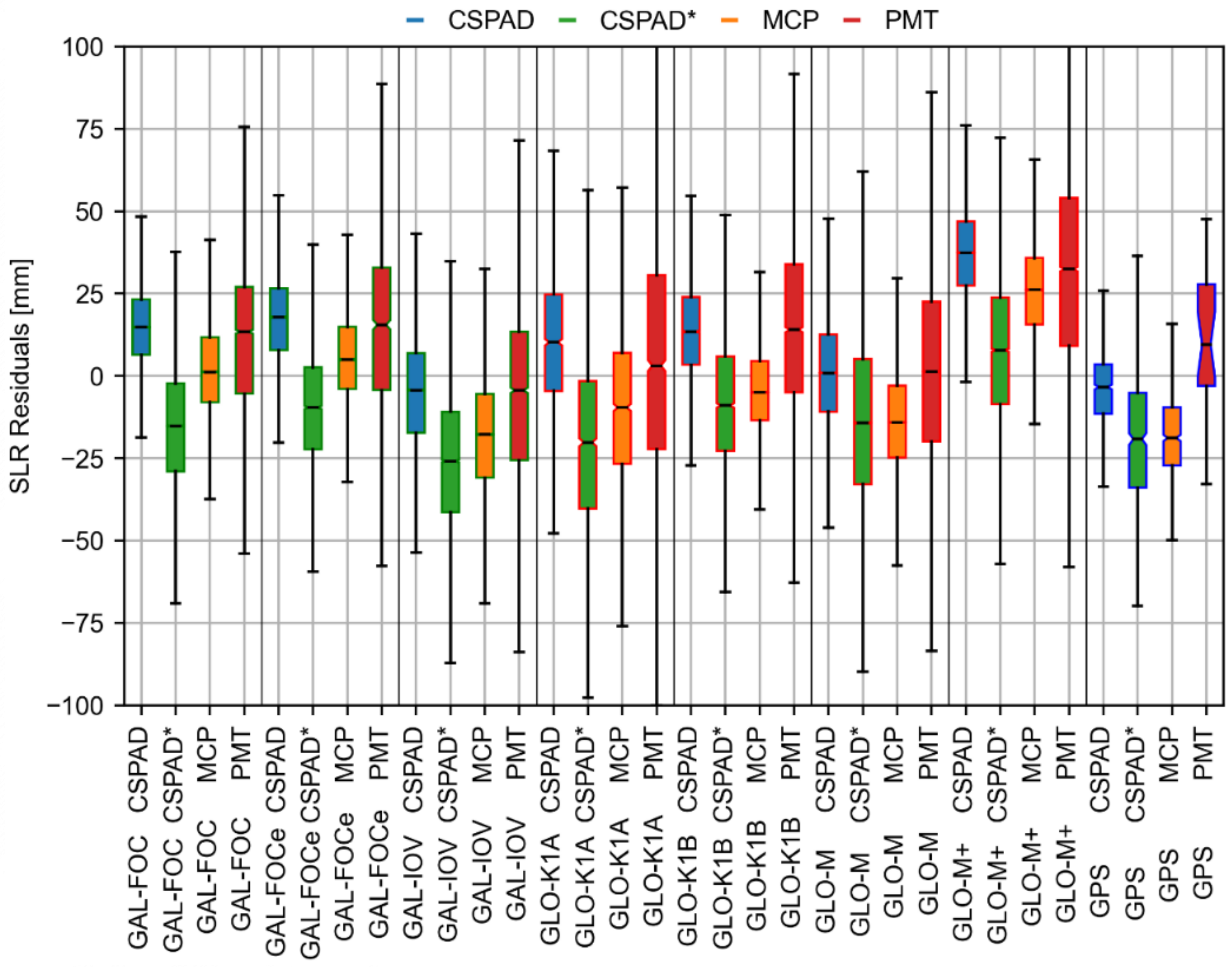
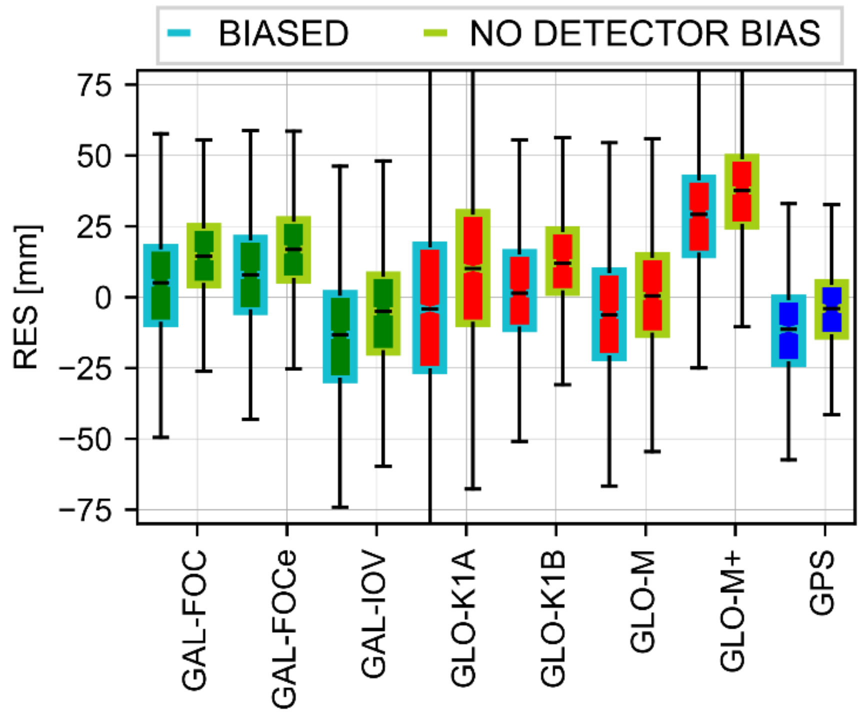
Handling detector-specific bias



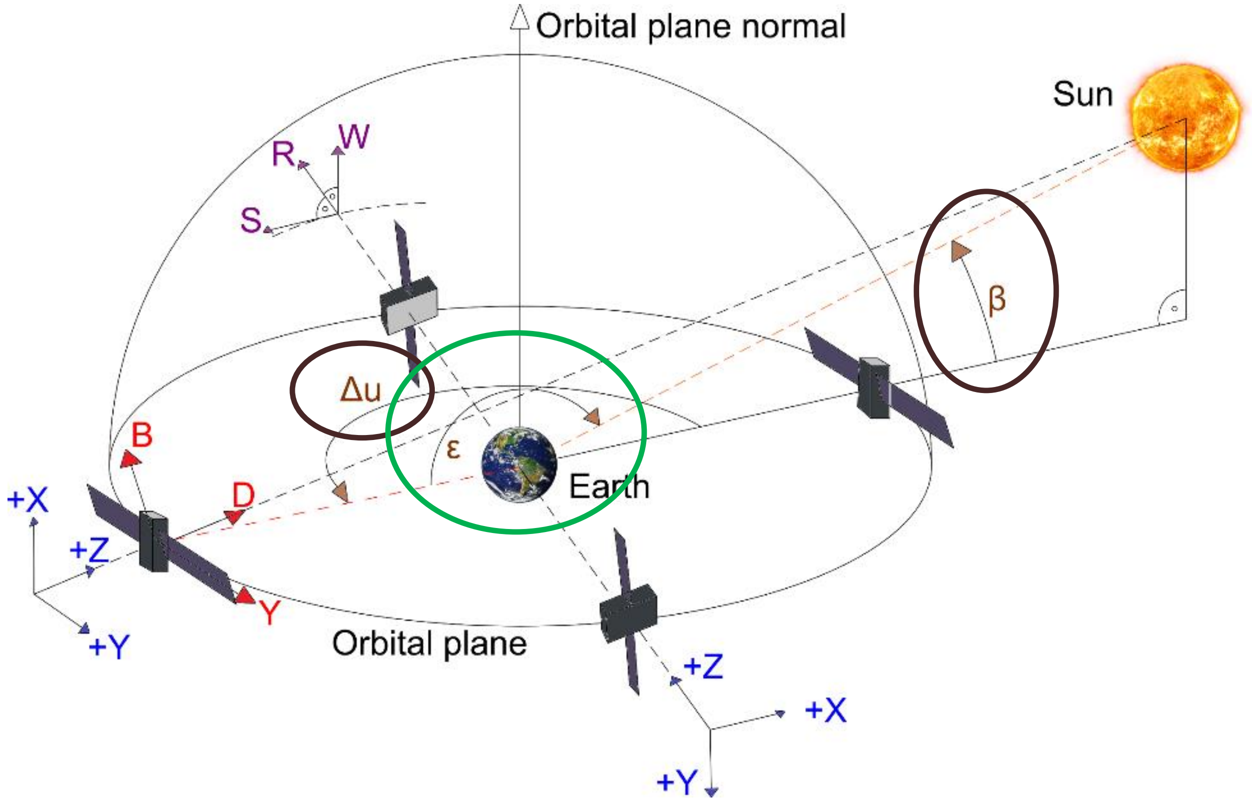
[mm]	CSPAD	CSPAD*	MCP	PMT
GAL-FOC	0	-30	-12	-4
GAL-FOCe	0	-26	-11	-1
GAL-IOV	0	-20	-13	0
GLO-K1A	0	-30	-19	-6
GLO-K1B	0	-22	-16	1
GLO-M	0	-15	-14	0
GLO-M+	0	-30	-11	-6
GPS	0	-14	-14	15



SLR validation of GNSS orbits

- SLR validation of the Combined orbits + individual ACs

- Searching for patterns in SLR residuals in different satellite-Sun-Earth geometry
  - SLR residuals as a function of β and argument of latitude of the satellite with respect to the argument of the latitude of the Sun (Δu),
  - SLR residuals as a function of elongation angle (ε)



satellite-Sun-Earth geometry