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Yebes, Spain
RECONNECTING THE ILRS COMMUNITY

Australian Government
Geoscience Australia

WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

SLR validation of IGS GNSS orbits derived in the framework of the ITRF2020 realization

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ITRF2020 – IGS contribution

	COD	ESA	GFZ	GRG	JPL	MIT	NGS	TUG	ULR	WHU
GNSS (included from)	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 (1994/01/02)	GPS (1994/01/01) GLO (2009/01/01) GAL (2013/01/01)	GPS (2003/01/01)	GPS (2008-01-01) GLO (2010-09-28)
Observable types	double differenced iono-free combinations GPS & GLONASS: L1 & L2 GALILEO: E1 & E5a	undifferenced iono-free linear combinations GPS & GLONASS: L1 & L2 GALILEO: E1 & E5a	undifferenced iono-free linear combinations	undifferenced ionosphere-free linear combination on carrier phase (and code). GPS and GLONASS : L1/L2 ; GALILEO : E1/E5a	undifferenced ionosphere-free linear combination. GPS: L1/L2	GPS L1&L2; GALILEO E1&E5a (dual frequency combination)	?	raw (undifferenced and uncombined) code and phase observations GPS: L1, L2, L5 GLONASS: L1, L2 Galileo: L1, L5, L7, L8	doubly differenced phase (GPS: L1&L2) and code observations	undifferenced iono-free linear combinations GPS and GLONASS : L1/L2
A priori solar radiation pressure	GPS & GLO: None GALILEO: Box-wing based on GSA(2019)	Box-wing models for all satellites used for: Solar Radiation Earth Reradiation Earth IR radiation	None	Box-wing models	GSPM13b (Sakumura et al 2017); GPS Block III: Manufacturer Table	Direct only	?	Box-wing models	Direct only	None
Empirical accelerations (constraints)	D,Y,B constants + B 1/rev + D 2/rev; no constraints for GALILEO if beta<12: + D 1/rev + Y constant (FOC only)	D, Y, B constants + B 1/rev + Along 1/rev. Along 1/rev constraint	D,Y,B constants + B 1/rev + D 2&4/rev; no constraints	ECOM2 model, without adjusting the bias in the sun direction	Solar Scale and Y Bias	ECOM2 with stochastic constraints and selected terms	?	7 ECOM2 parameters (D0, D2, Y0, B0, B1), no constraints	ECOM2 with stochastic constraints and selected terms	7 ECOM2 parameters (D0, D2, Y0, B0, B1), no constraints
Stochastic pulses (constraints)	pseudo-stochastic at midnight	None	at 12:00	For each eclipsing satellite	None	None	?	at center of day (12:00),	None	

- 10 IGS Analysis Centers provided GNSS solutions employing different orbit modeling and observables
- For the first time, in ITRF three GNSS systems are included: GPS, GLONASS, Galileo

ITRF2020 – IGS contribution

	COD	ESA	GFZ	GRG	MIT	TUG
GNSS (included from)	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 (2000-01-02) GAL (2017-01-01)	GPS (1994/01/01) GLO (2009/01/01) GAL (2013/01/01)
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A priori solar radiation pressure	GPS & GLO: None GALILEO: Box-wing based on GSA(2019)	Box-wing models for all satellites used for: Solar Radiation Earth Reradiation Earth IR radiation	None	Box-wing models	Direct only	Box-wing models
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Stochastic pulses (constraints)	pseudo-stochastic at midnight	None	at 12:00	For each eclipsing satellite	None	at center of day (12:00),

- 10 IGS Analysis Centers provided GNSS solutions employing different orbit modeling and observables
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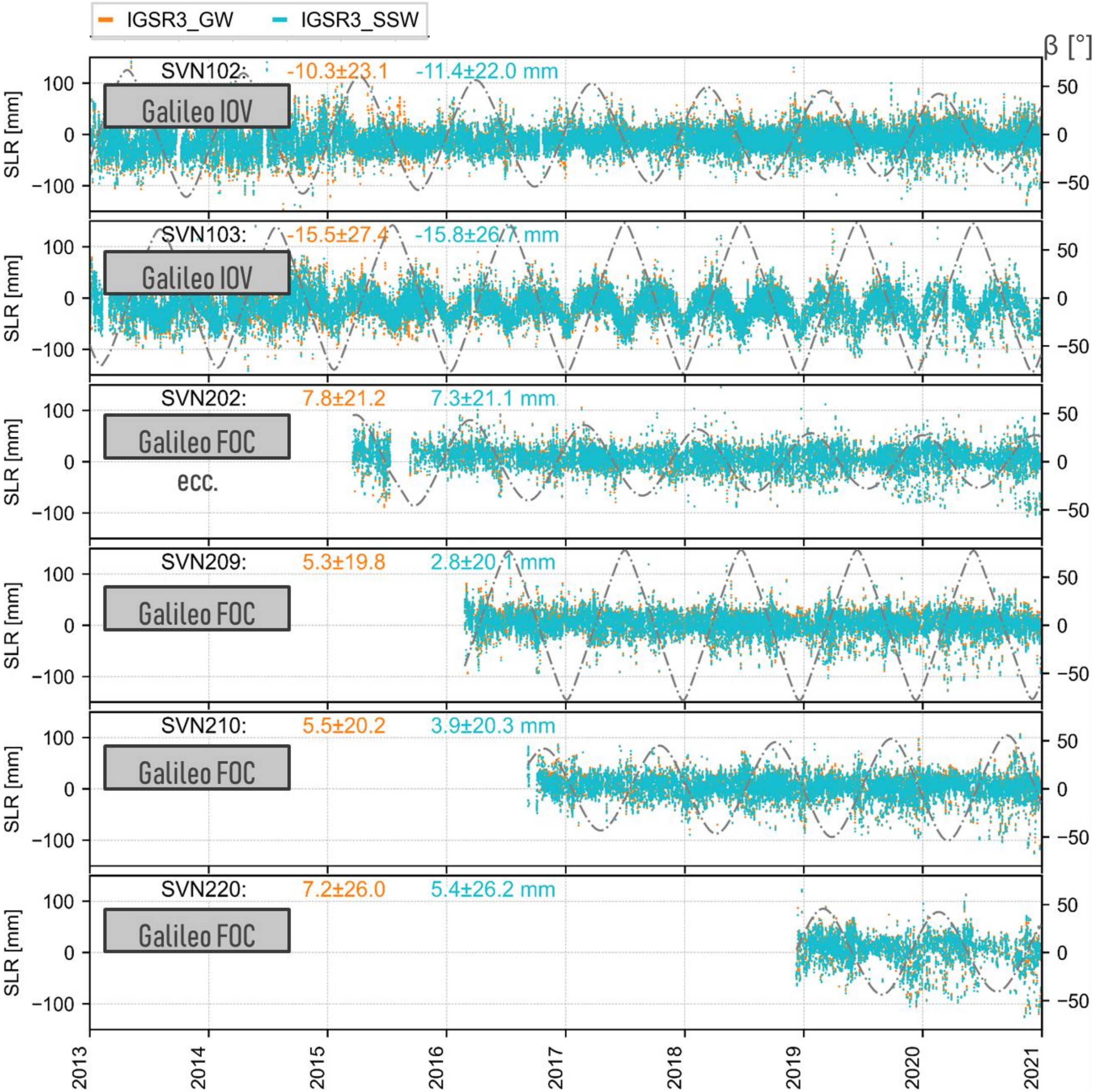
SLR validation of GNSS orbits

- Validation of the **combined** IGS Repro3 orbits delivered by Geoscience Australia using Satellite Laser Ranging (SLR) data:
  - Traditional global AC weighting algorithm (**GW**)
  - Satellite-specific AC weighting algorithm (**SSW**)

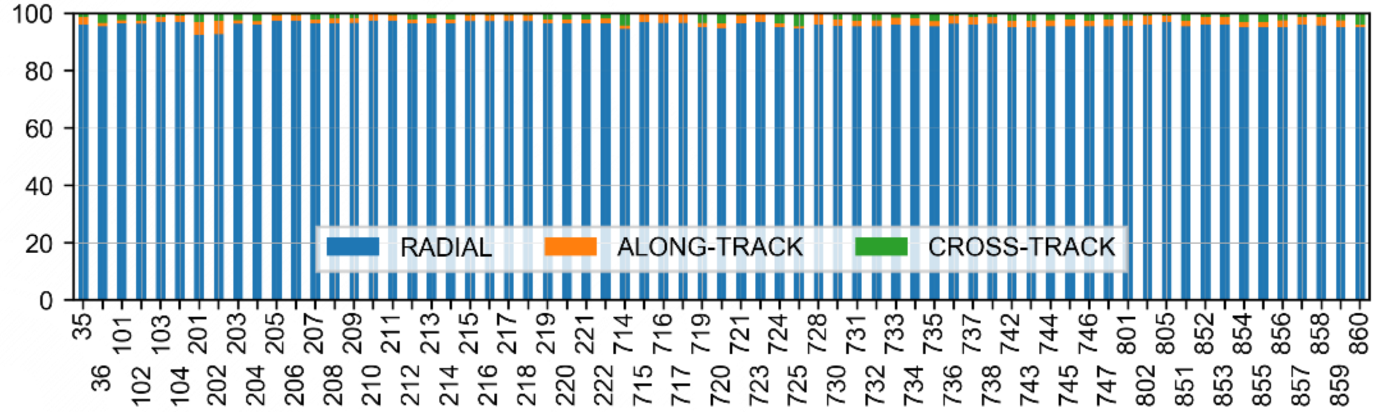
- Dataset 2013-2020 (main interest in Galileo)

- SLR validation of different satellite types: Galileo FOC, FOC eccentric orbit, IOV, GLONASS-M, -K

Combination strategy:
Sośnica K., Zajdel R., Bury G., Bosy J., Moore M., Masoumi S. (2020) ***Quality assessment of experimental IGS multi-GNSS combined orbits*** GPS Solutions, Vol. 24 No. 54,
URL: https://link.springer.com/article/10.1007/s10291-020-0965-5

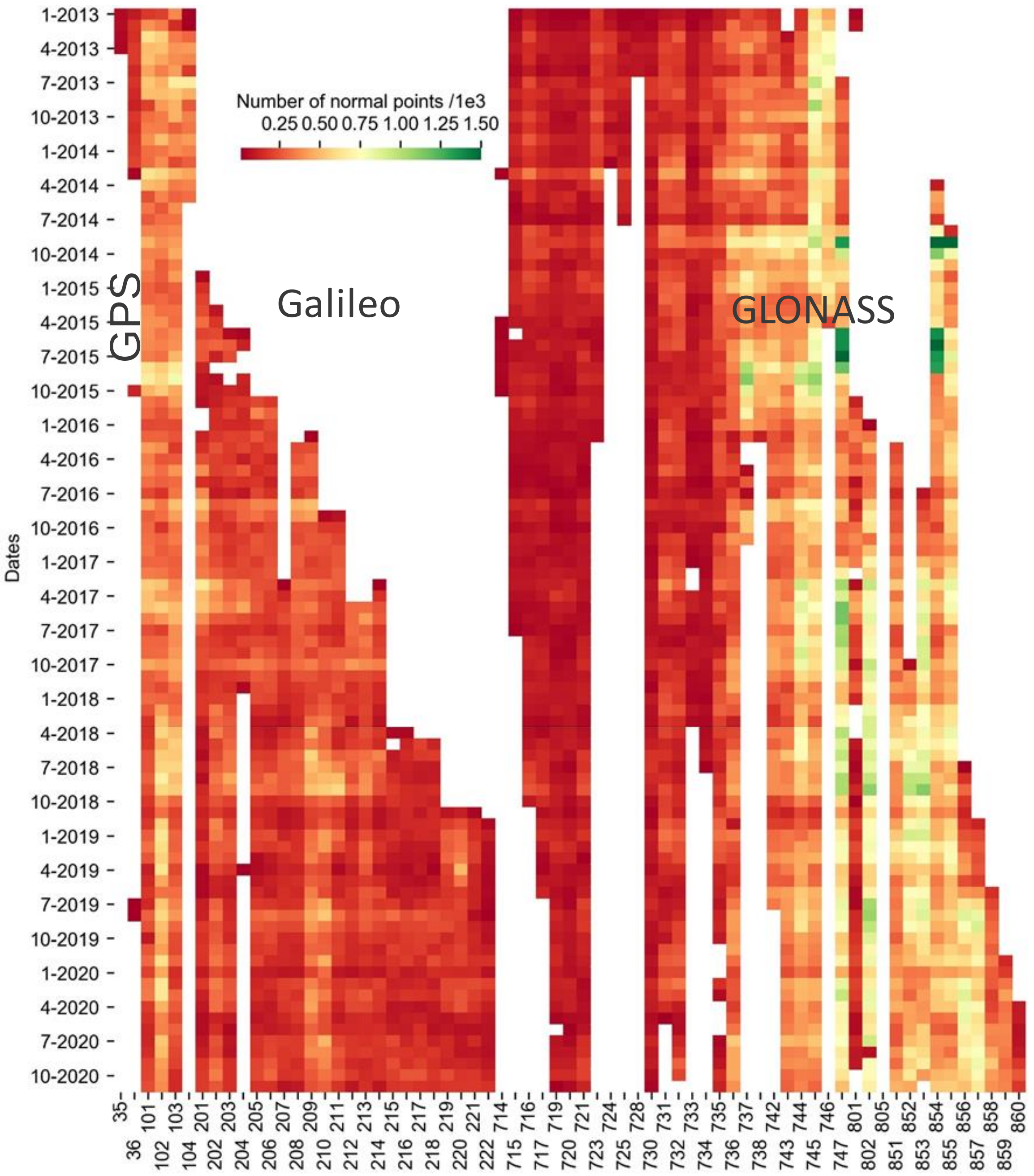


No. of observations

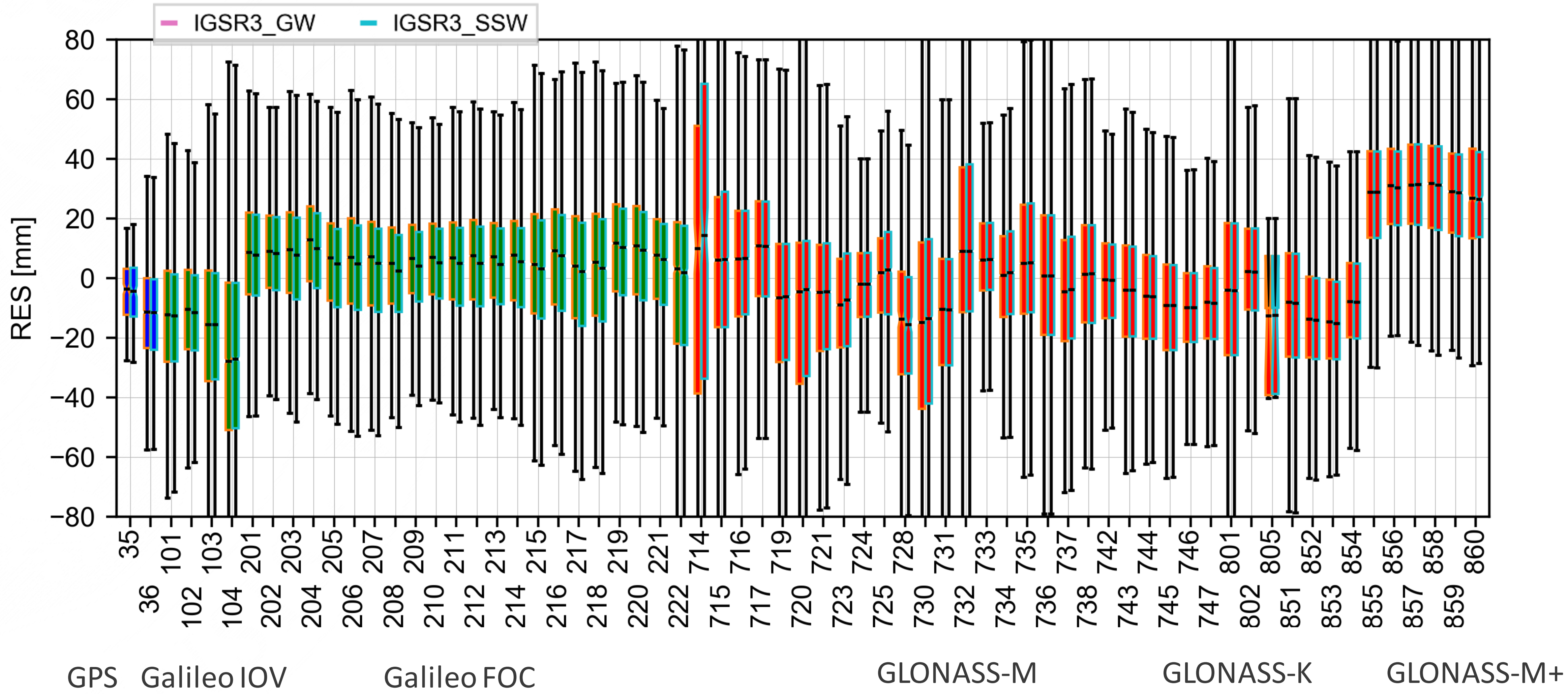


- SLR validation of the GNSS orbits is sensitive to the radial orbit direction (96%), however, it may also deliver some information about the along-track (2.1%) and cross track component (1.9%)

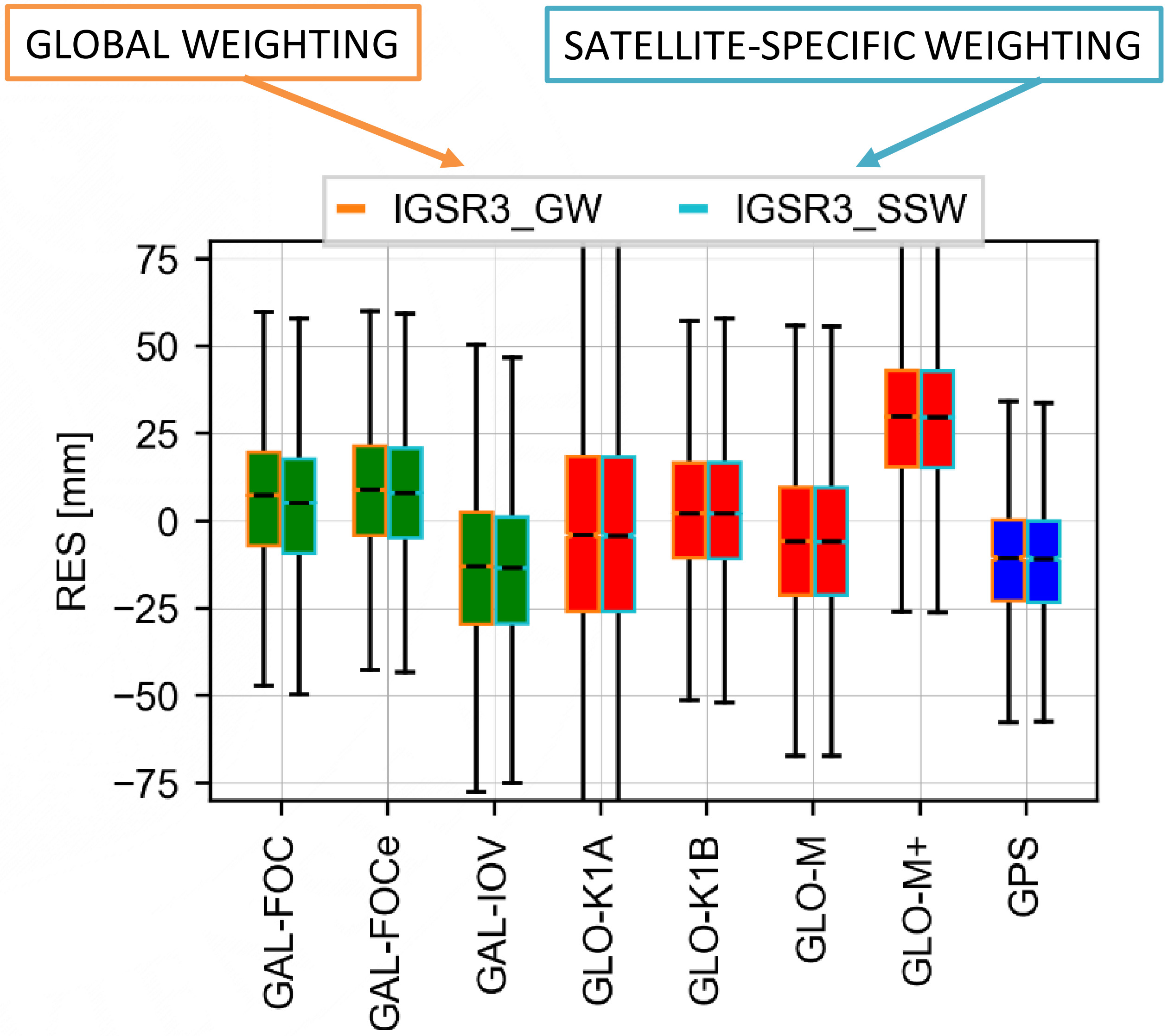
- For Galileo FOC in eccentric orbits (SVN 201, 202), the radial component is smaller than for other GNSS satellites (~90%)



SLR validation of GNSS orbits



Results for different satellite types



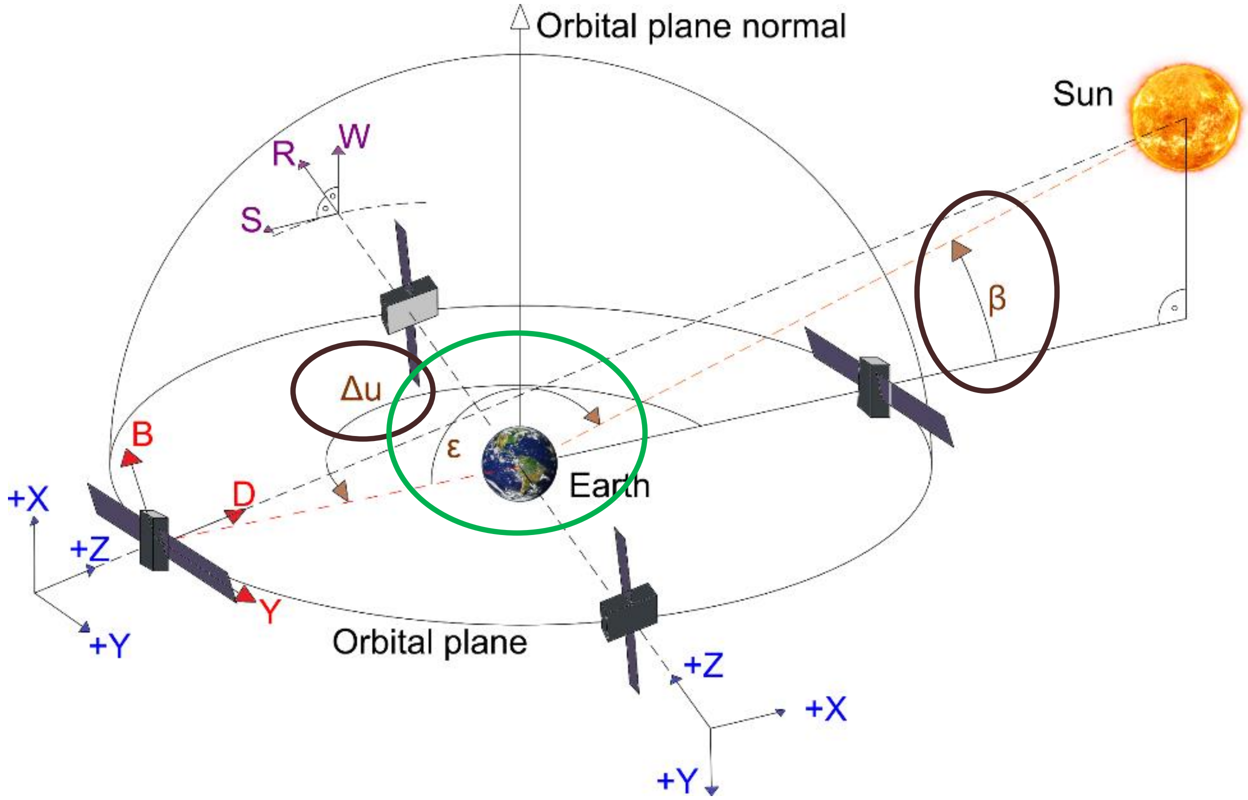
[mm]	MEAN		STD		RMS	
type	GW	SSW	GW	SSW	GW	SSW
GAL-FOC	5.2	3.0	24.1	24.0	24.7	24.9
GAL-FOCe	7.7	6.9	25.2	24.2	26.3	27.3
GAL-IOV	-14.1	-14.4	31.1	28.0	34.2	27.7
GLO-K1A	-2.9	-3.0	37.7	37.6	37.8	37.4
GLO-K1B	3.8	3.1	23.8	22.9	24.1	24.6
GLO-M	-5.5	-5.8	29.2	28.3	29.7	27.3
GLO-M+	28.7	27.6	25.8	24.0	38.6	43.1
GPS	-11.2	-11.7	23.2	20.3	25.8	19.5

- Improvement of SSW compared to GW

	MEAN [%]	STD [%]	RMS [%]
GAL-FOC	-39.2	0.0	-1.4
GAL-FOCe	-8.9	-1.8	-2.4
GAL-IOV	3.8	-7.2	-5.3
GLO-K1A	2.3	0.0	0.0
GLO-K1B	-0.2	0.1	0.1
GLO-M	0.3	0.6	0.6
GLO-M+	-1.0	0.1	-0.6
GPS	2.9	0.2	0.8

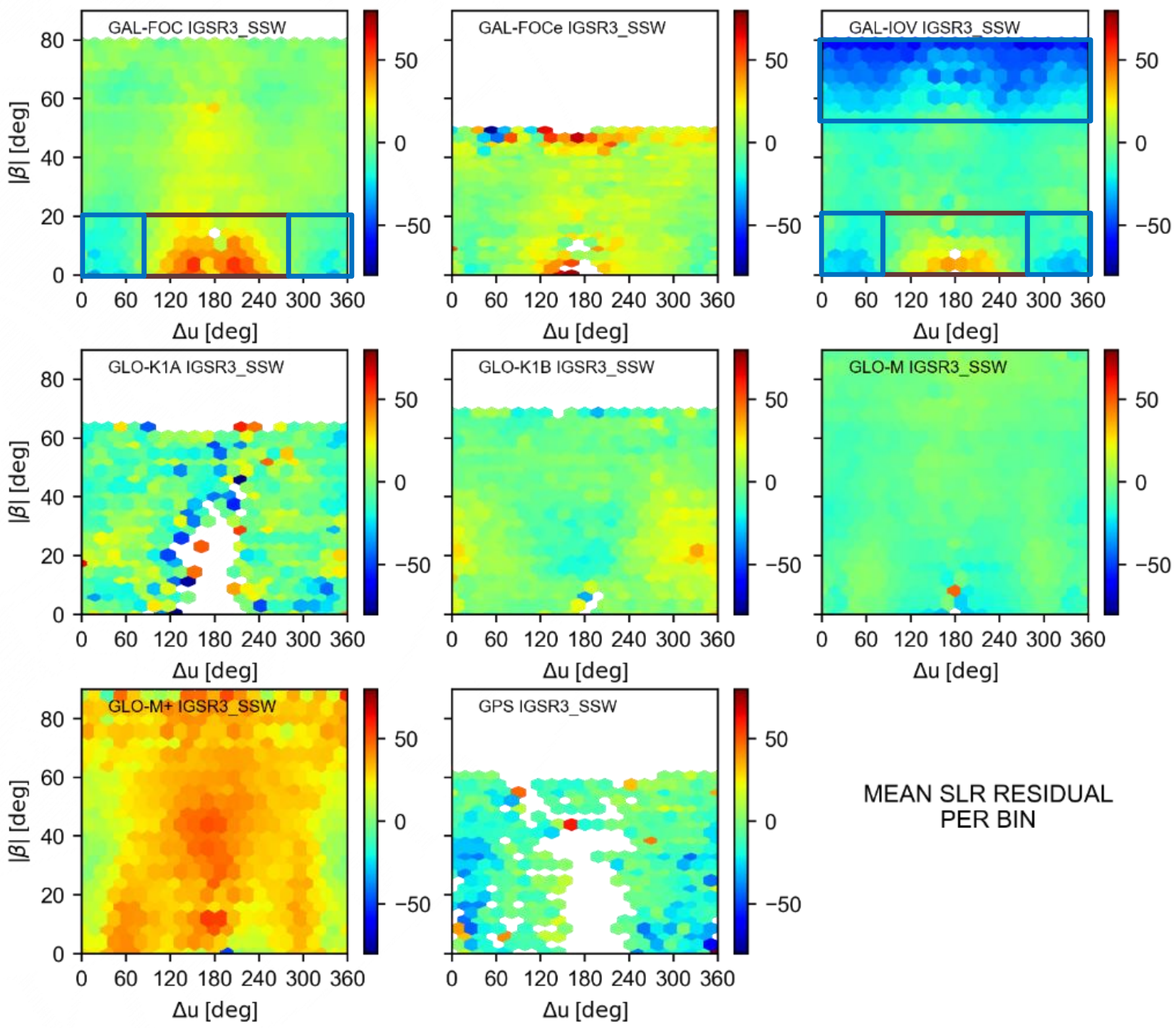
SLR validation of GNSS orbits

- 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)
- Possibilities to study SLR-related issues - Satellite signature effect



satellite-Sun-Earth geometry

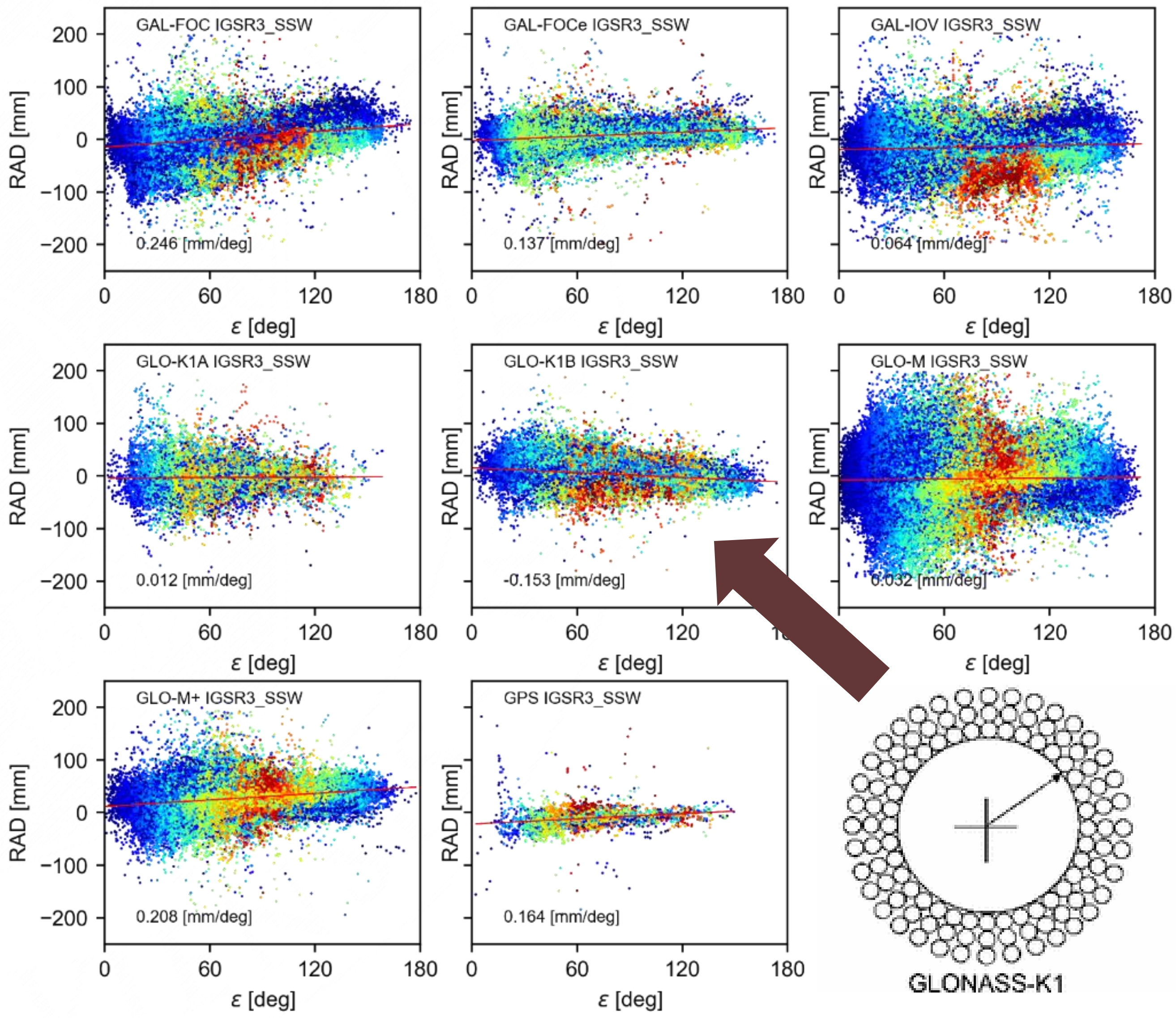
Orbit modeling issues - searching for patterns in SLR residuals (combined orbits)



SLR residuals as a function of <u>absolute β</u> and argument of latitude of the satellite with respect to the argument of latitude of the Sun (Δu)

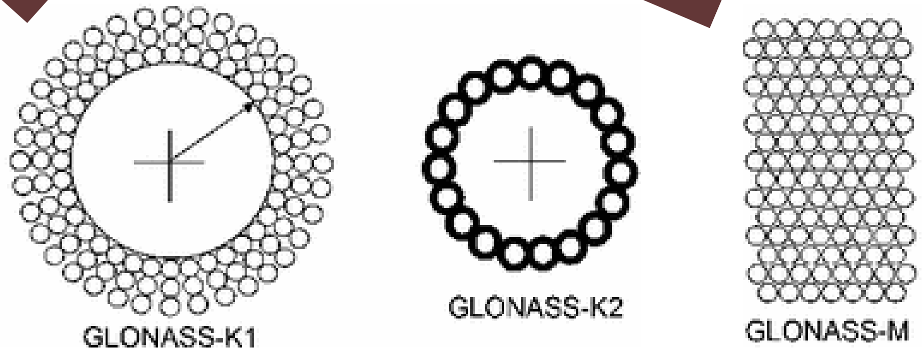
- Characteristic patterns for Galileo FOC (eclipsing seasons) and IOV satellites (eclipsing seasons and high β angles)
- Good quality for GLONASS-M and K1B

Orbit modeling issues - searching for patterns in SLR residuals

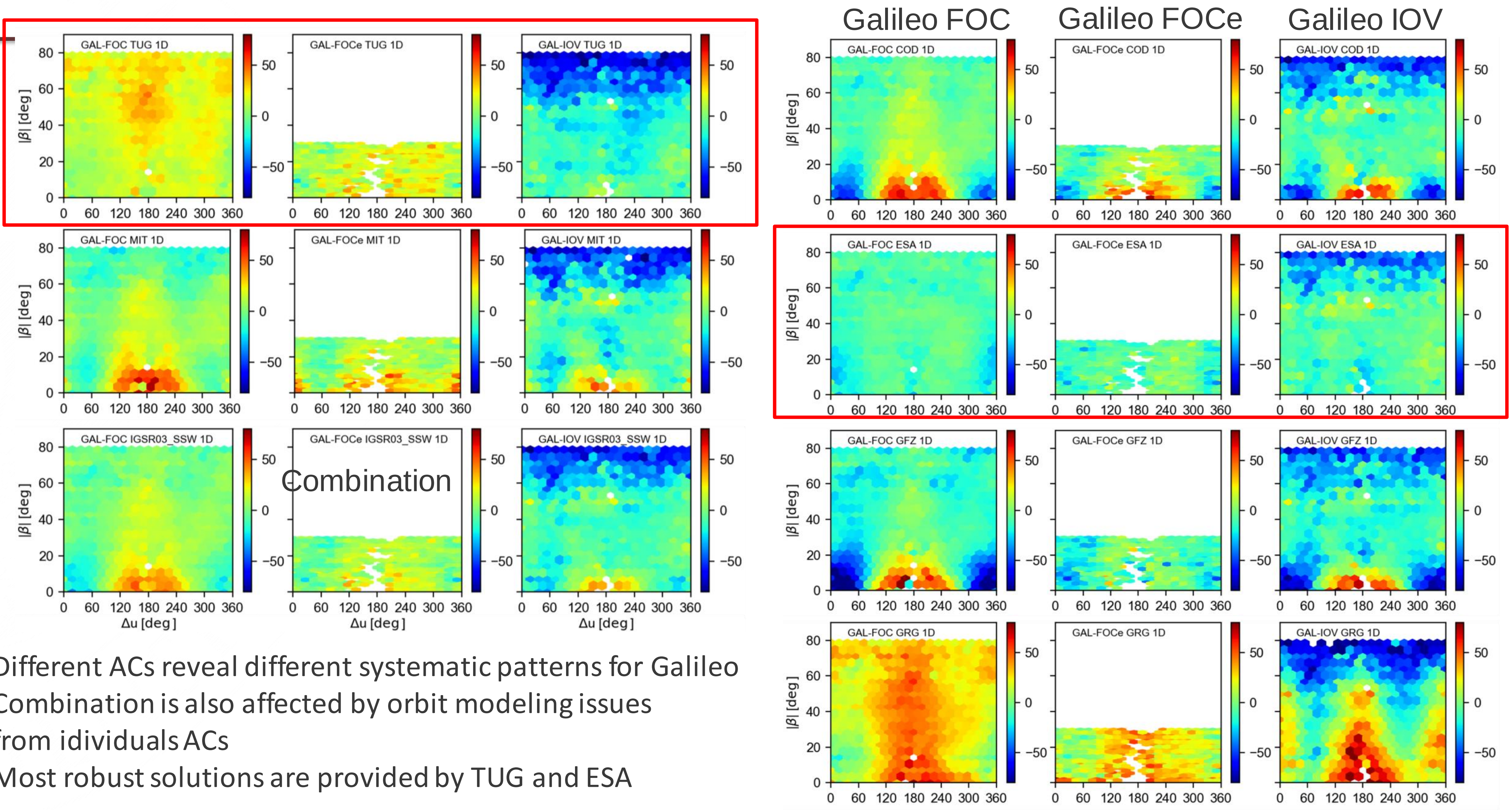


SLR residuals as a function of elongation angle (ε). Dots are colored with the absolute height of the Sun above the orbital plane (β)

- Linear dependency between the elongation angle (ε) and SLR residuals for Galileo FOC satellites with a slope of 0.25 (FOC), 0.14 (FOCe), -0.15 (K1B), and 0.21 mm/deg (M+).



Orbit modeling issues - searching for patterns in SLR residuals (individual ACs)



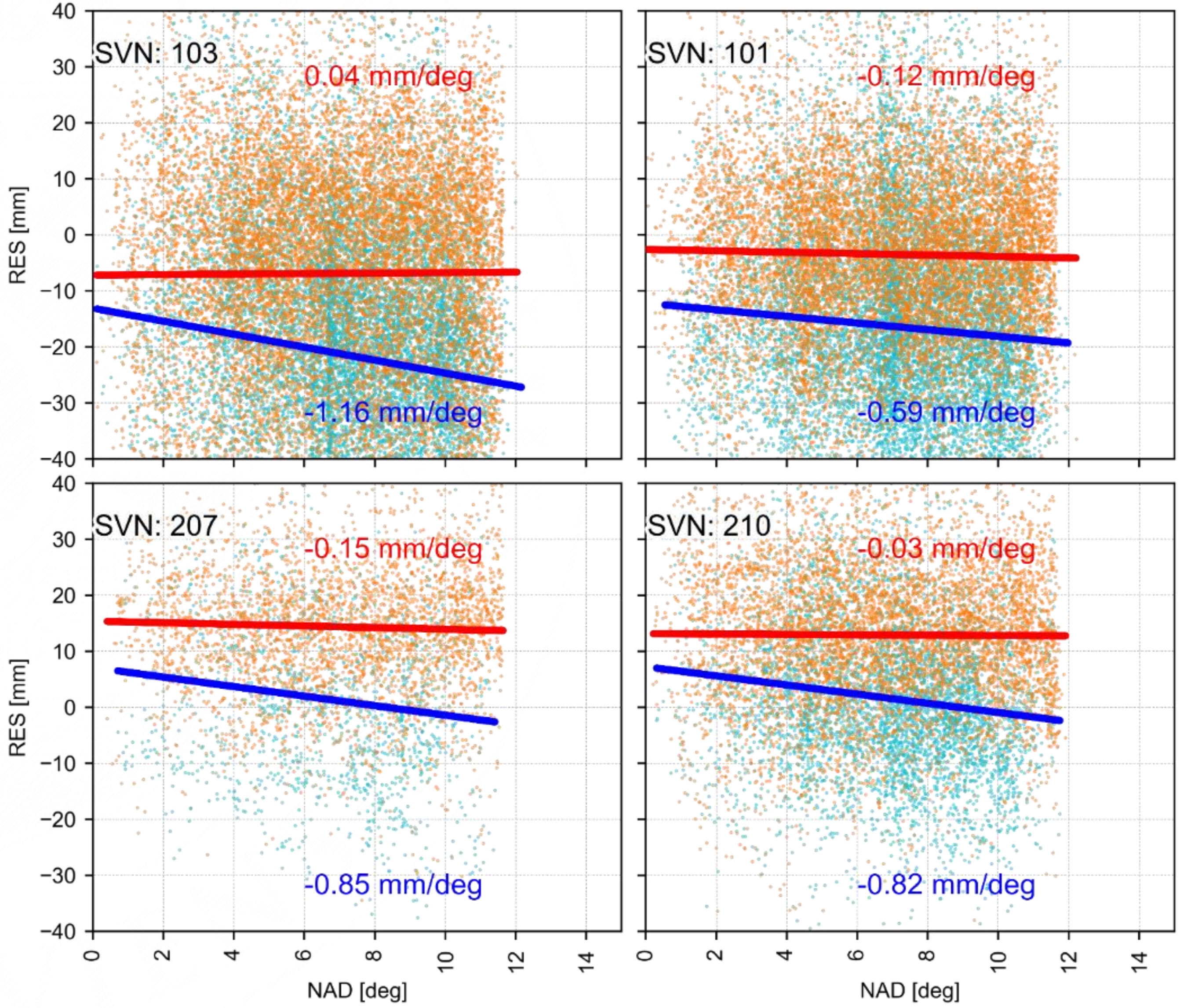
- Different ACs reveal different systematic patterns for Galileo
- Combination is also affected by orbit modeling issues from idividuals ACs
- Most robust solutions are provided by TUG and ESA

Orbit modeling issues - searching for patterns in SLR residuals (individual ACs)

-		GAL-FOC	GAL-FOCe	GAL-IOV	GLO-K	GLO-M	GLO-M+
COD	mean SLR offset mm]	-6.4	-2.9	-12.4	-7.6	-6.8	28.0
ESA		-10.7	-8.9	-8.3	4.3	-6.6	28.4
GFZ		-19.4	-12.2	-19.1	14.4	-8.2	24.5
GRG		22.8	17.0	5.0	1.1	-1.3	35.8
MIT		2.7	9.1	-9.1	-	-	-
TUG		17.4	14.6	-16.5	2.0	-10.6	24.0
GW		3.0	4.6	-10.0	1.7	-6.2	28.5
SSW		0.8	4.1	-11.6	1.7	-6.4	28.1
COD	Standard dev. [mm]	28.8	28.5	29.1	26.6	34.4	28.1
ESA		24.4	25.6	23.1	25.2	31.7	25.9
GFZ		33.2	28.7	30.9	28.8	38.9	32.8
GRG		28.9	29.6	35.8	27.1	35.3	30.8
MIT		27.1	26.7	27.8	-	-	-
TUG		24.2	25.5	26.0	24.6	34.7	29.3
GW		25.3	25.3	25.5	26.9	32.9	26.9
SSW		25.4	25.3	25.0	26.9	32.8	26.9

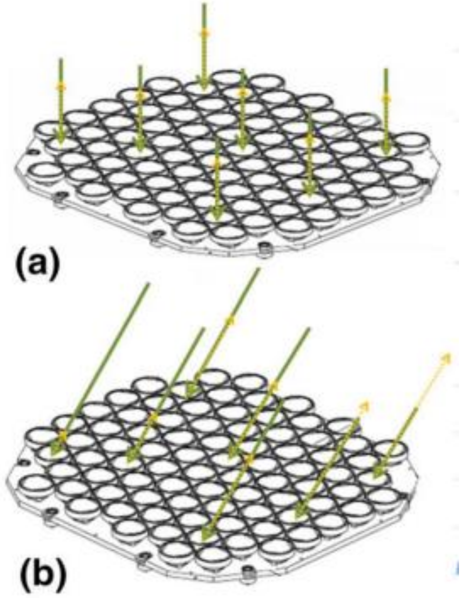
- Some ACs provide better solutions than the combination in terms of the standard deviation of SLR residuals.
- SLR is a very valuable tool to discover systematic effects in orbits as well as GNSS modeling issues.

Possibilities to study SLR-related issues - satellite signature effect



SLR residuals as a function of nadir angle for multi-photon MCP and single-photon CSPAD

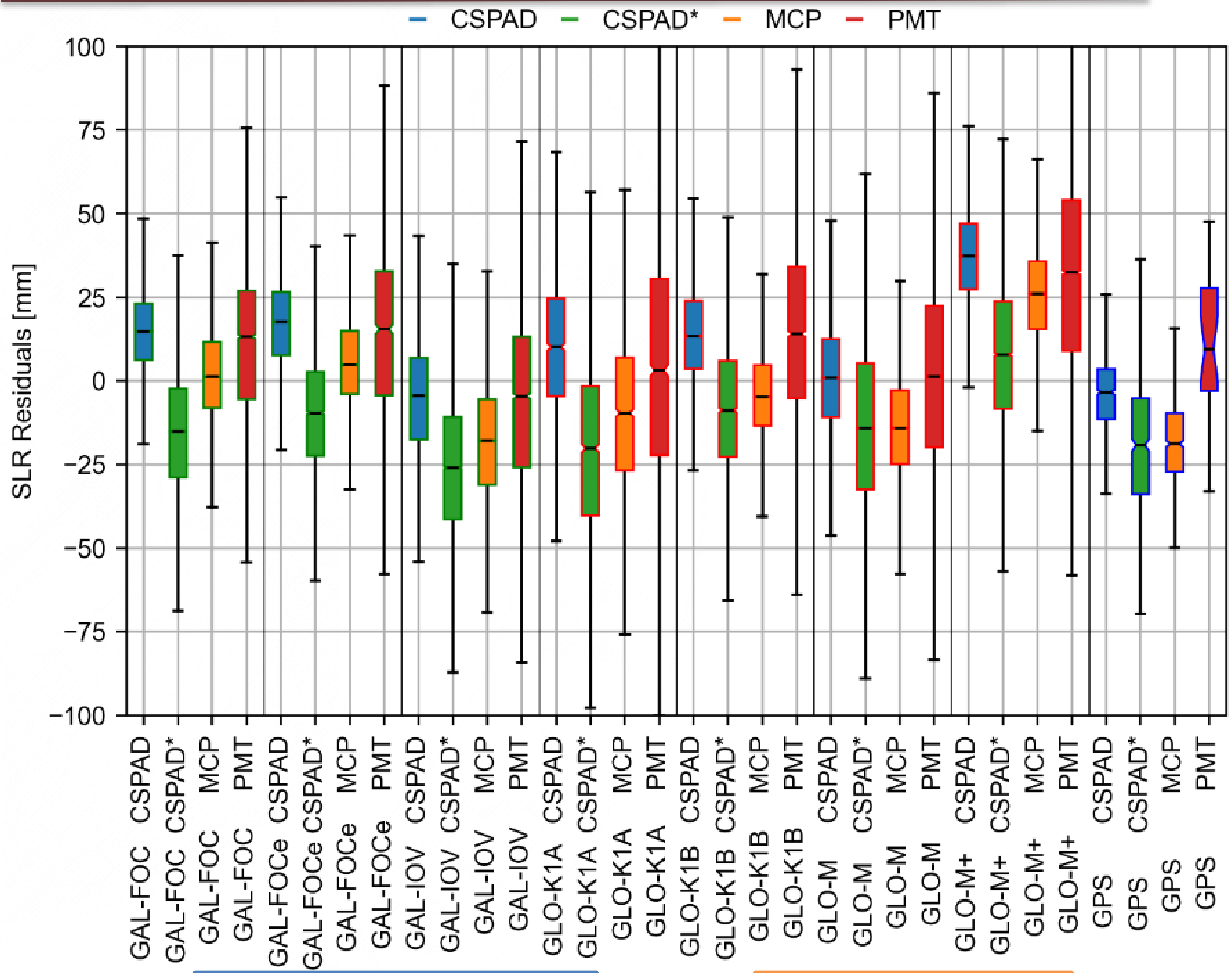
When taking SLR observations from the stations equipped with MCP detectors a linear dependency between the SLR residuals and nadir angle („satellite signature effect”) is visible **(Mostly for Galileo IOV – large LRA)**



Nadir = 0°

Nadir = 15°

Possibilities to study SLR-related issues



CSPAD: European stations

CSPAD*: Chinese stations

MCP: NASA stations

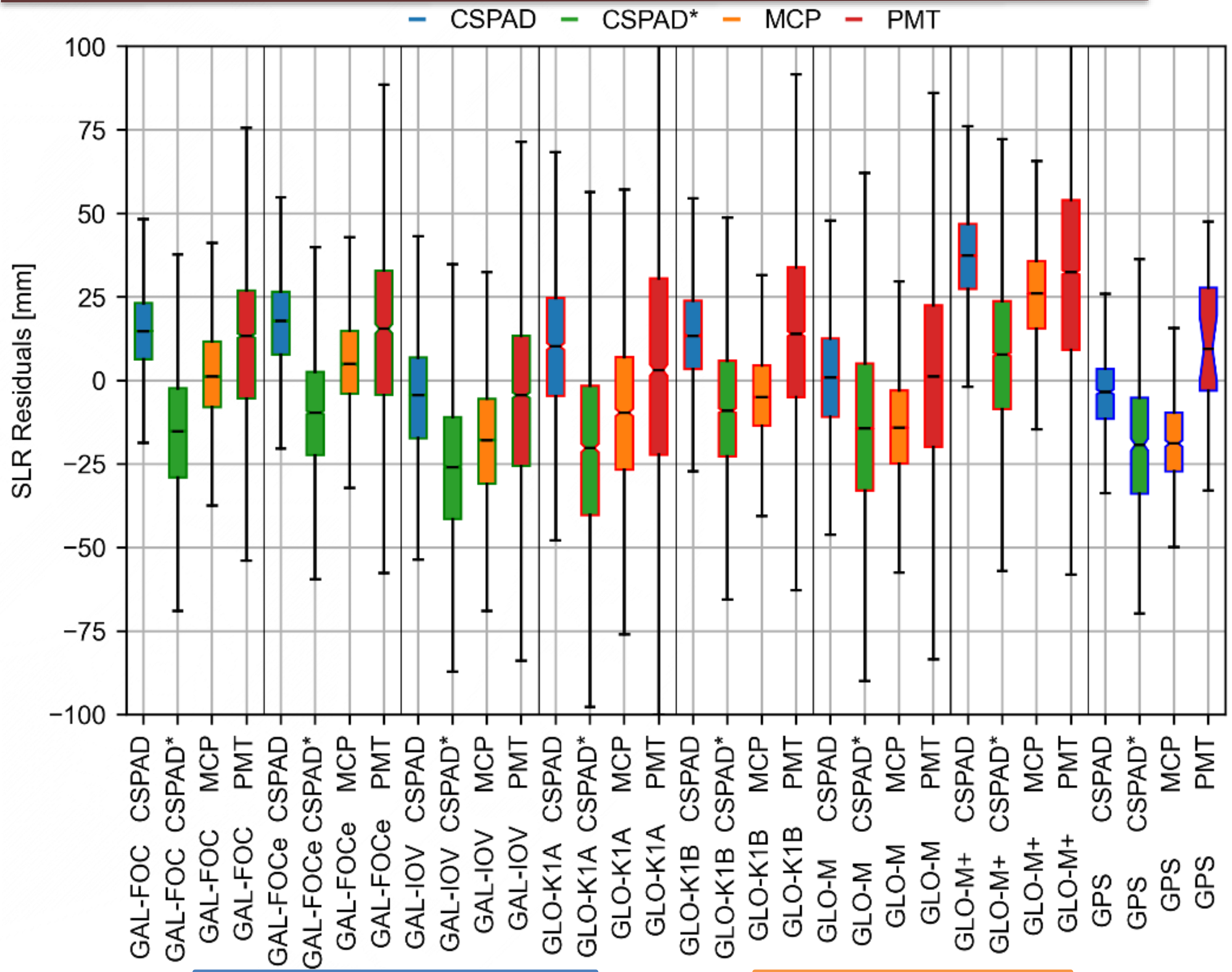
PMT: Russian stations

Type	Detector	Mean [mm]	Number of normal points
GAL-FOC	**CSPAD**	14.8	67835
	CSPAD*	-16.7	42940
	MCP	2.1	43968
	PMT	10.7	6729
GAL-FOCe	**CSPAD**	16.9	10621
	CSPAD*	-10.9	6034
	MCP	5.3	10198
	PMT	15.5	1604
GAL-IOV	**CSPAD**	-5.5	39480
	CSPAD*	-25.9	14629
	MCP	-18.2	42815
	PMT	-5.9	5423

There are some substantial differences (2 cm) in the mean offset of SLR residuals when considering SLR observations from different stations.

Long time-series of the uniform in quality GNSS orbits allow for the study of detector-specific issues in Satellite Laser Ranging to the GNSS satellites.

Possibilities to study SLR-related issues



CSPAD: European stations

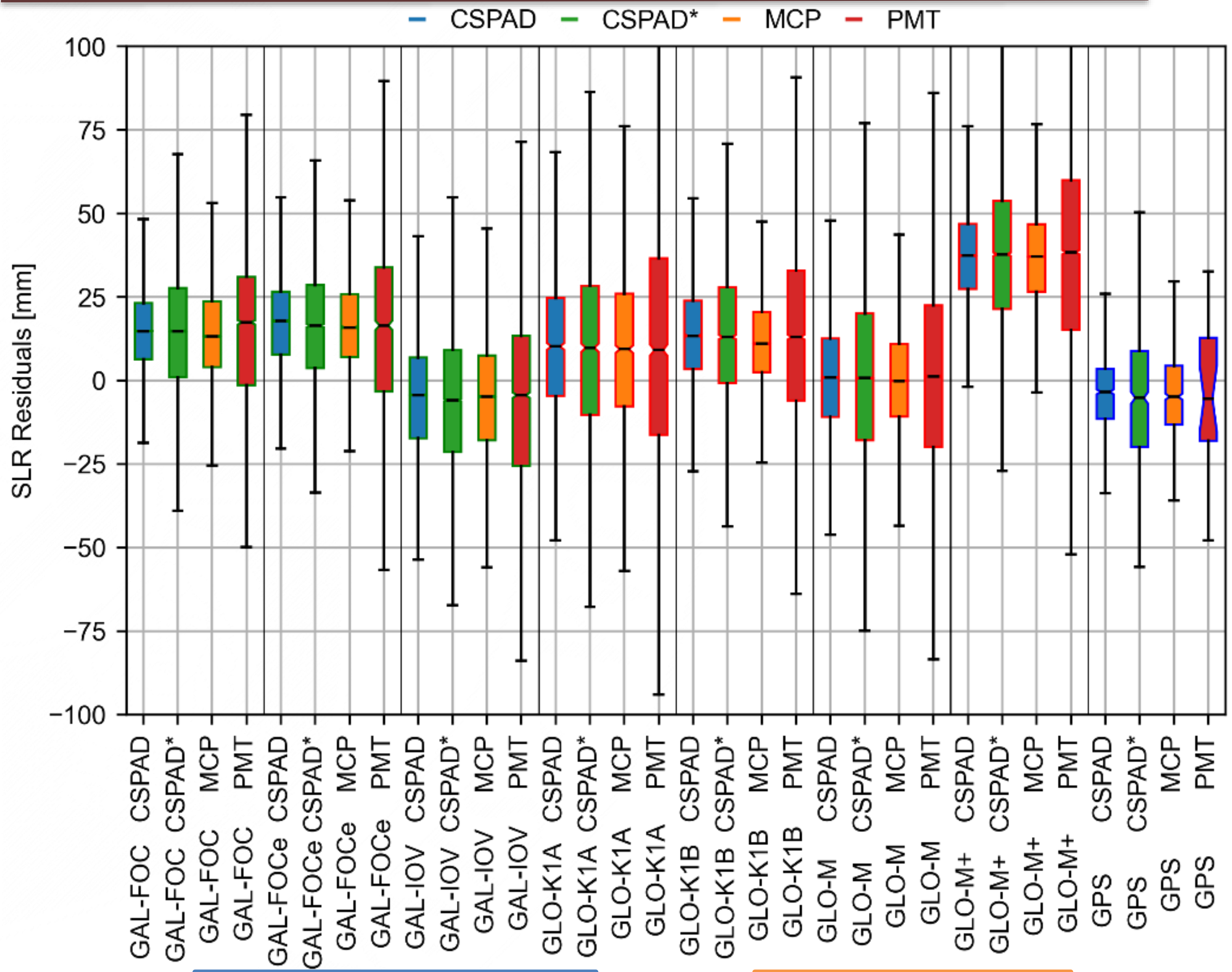
MCP: NASA stations

CSPAD*: Chinese stations

PMT: Russian stations

type	det	count	mean [mm]	std [mm]
GAL-FOC	**CSPAD**	69018	15	**14**
	CSPAD*	43337	-17	25
	MCP	44573	2	**16**
	PMT	6761	11	28
GAL-FOCe	**CSPAD**	10803	17	**15**
	CSPAD*	6141	-11	24
	MCP	10329	5	**16**
	PMT	1618	15	29
GAL-IOV	CSPAD	40028	-5	20
	CSPAD*	14788	-26	28
	MCP	43239	-18	22
	PMT	5472	-6	30
GLO-K1B	**CSPAD**	10441	14	**16**
	CSPAD*	4579	-9	25
	MCP	18469	-4	**15**
	PMT	6040	14	31
GLO-M	CSPAD	183065	1	20
	CSPAD*	94354	-14	33
	MCP	138225	-14	18
	PMT	84022	1	33
GLO-M+	**CSPAD**	24036	37	**15**
	CSPAD*	10560	6	27
	MCP	28229	25	**15**
	PMT	11998	31	33
GPS	**CSPAD**	1037	-4	**12**
	CSPAD*	619	-18	21
	MCP	816	-18	**14**
	PMT	24	11	22

Possibilities to study SLR-related issues



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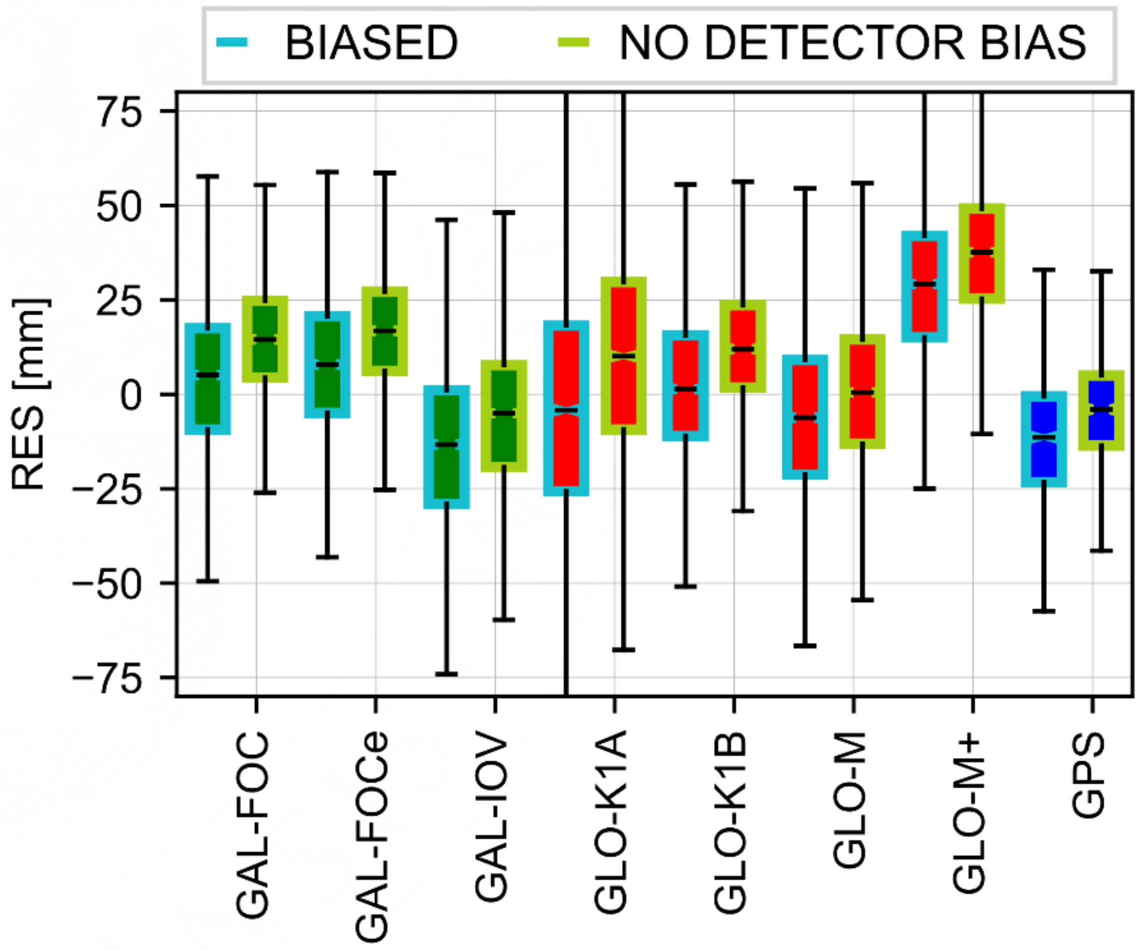
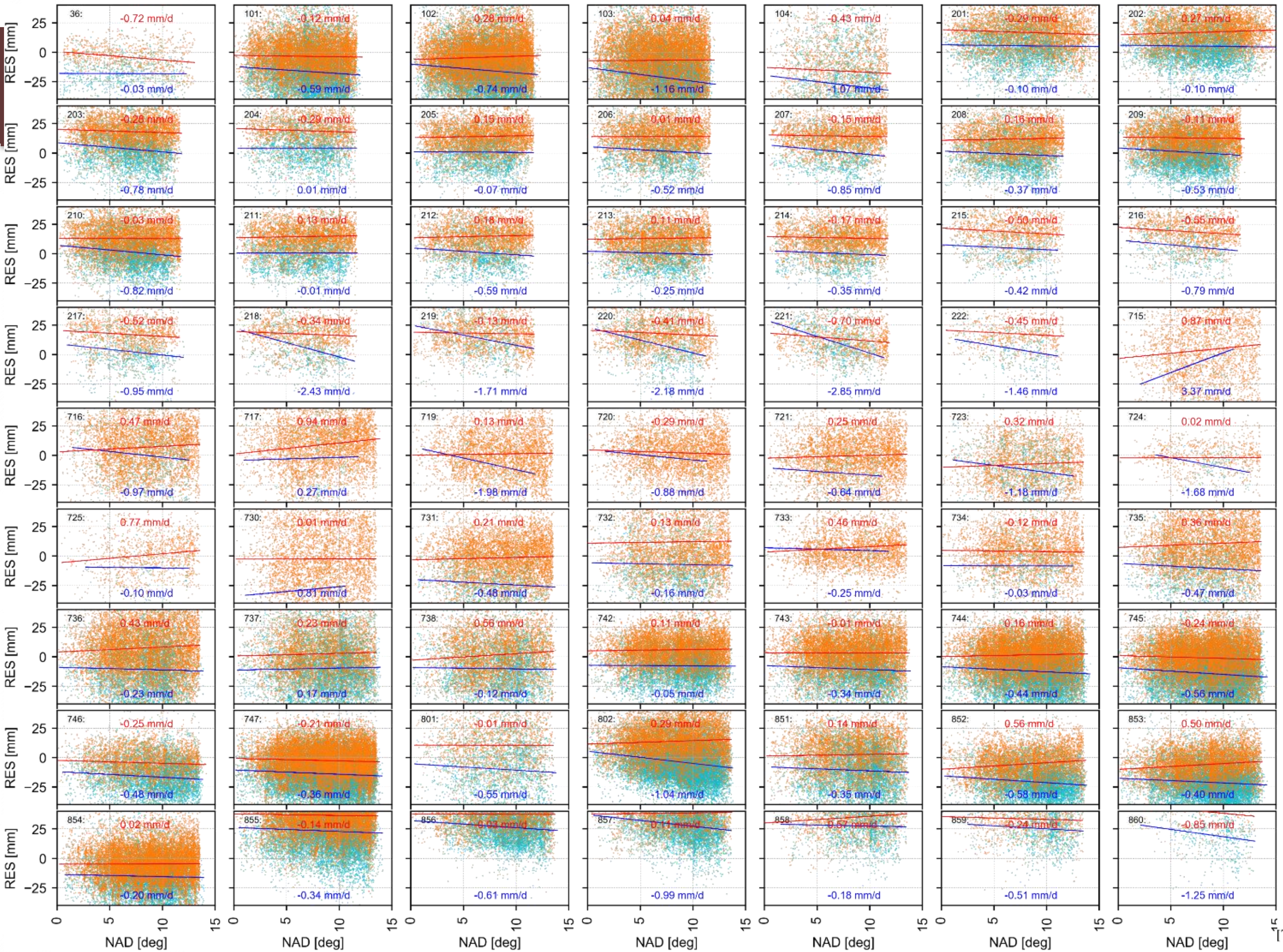
Possibilities to study SLR-related issues



[mm]	MEAN		STD		RMS	
type	BIAS	NDB	BIAS	NDB	BIAS	NDB
GAL-FOC	3.0	14.4	24.0	**20.3**	24.2	24.9
GAL-FOCe	6.9	16.4	24.2	**21.8**	25.1	27.3
GAL-IOV	-14.4	-6.1	28.0	**27.0**	31.5	27.7
GLO-K1A	-3.0	11.3	37.6	**35.7**	37.7	37.4
GLO-K1B	3.1	13.0	22.9	**20.9**	23.1	24.6
GLO-M	-5.8	0.9	28.3	**27.3**	28.9	27.3
GLO-M+	27.6	37.0	24.0	**22.1**	36.6	43.1
GPS	-11.7	-3.8	20.3	**19.1**	23.5	19.5

- Improvement of NDB compared to BIAS

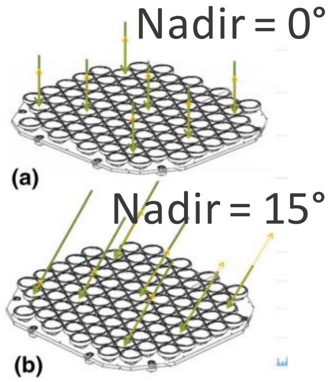
	MEAN [%]	STD [%]	RMS [%]
GAL-FOC	374.4	-15.2	3.2
GAL-FOCe	137.6	-9.9	8.4
GAL-IOV	-57.5	-3.7	-12.2
GLO-K1A	-473.0	-5.1	-0.9
GLO-K1B	318.4	-8.7	6.5
GLO-M	-115.0	-3.4	-5.4
GLO-M+	34.0	-7.9	17.8
GPS	-67.5	-5.9	-16.9



SLR residuals as a function of nadir angle for MCP and single-photon CSPAD

When taking SLR observations from the stations equipped with MCP detectors we see a linear dependency between the SLR residuals and nadir angle („satellite signature effect")

Mostly visible for Galileo IOV



Conclusions

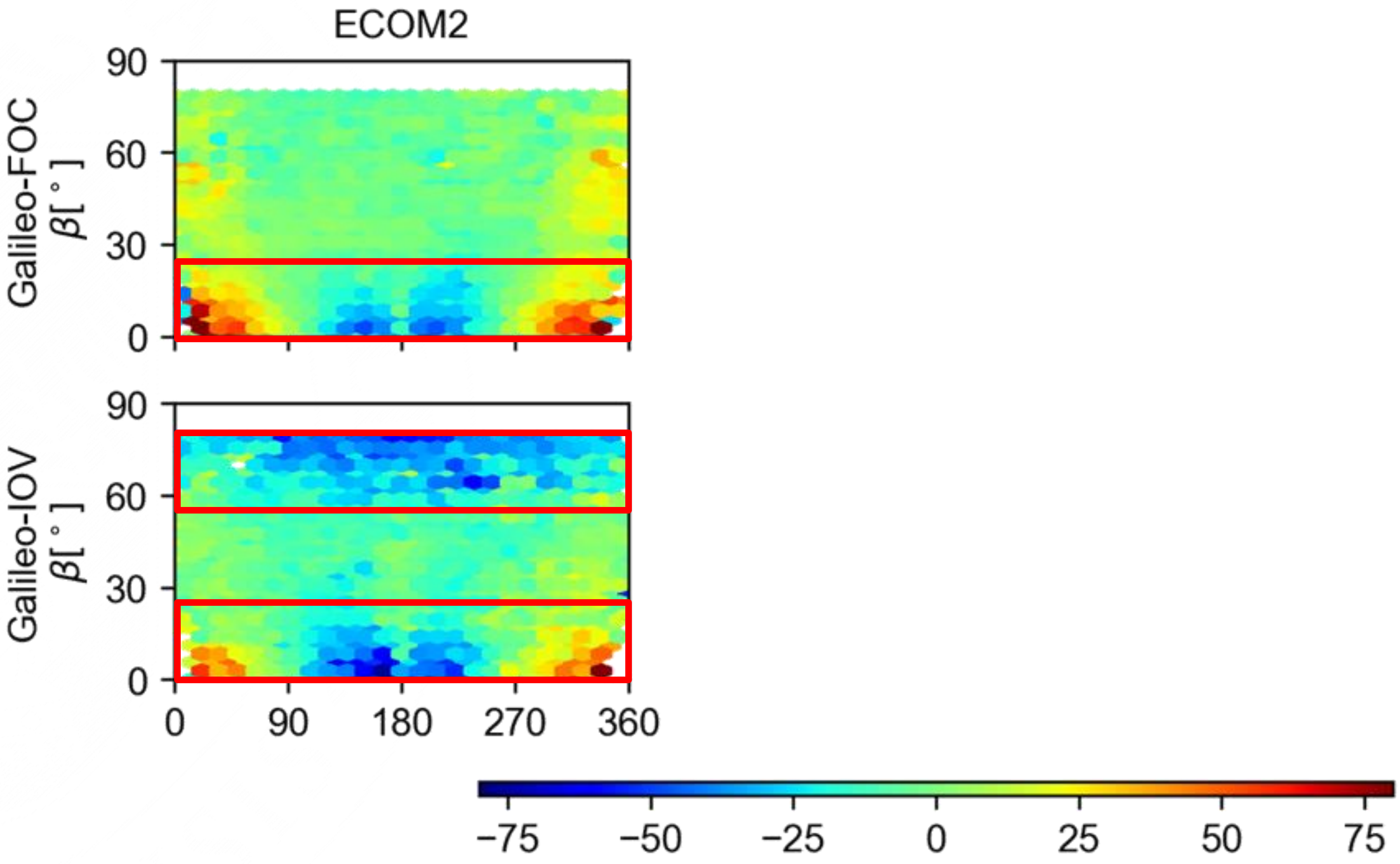
- For the first time, three GNSS systems contribute to the ITRF realization. SLR is an independent tool to validate the quality of GNSS orbits: Galileo and GLONASS.
- **The standard deviation of SLR residuals is at the level of 25 mm, but after removing detector-specific errors, it can be reduced to 12-16 mm.**
- Analysis of SLR residuals in Sun-Earth-satellite frame 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); thus, there is still space for improvement in the combination strategy.
- **Large differences between single-photon and multi-photon detectors have been found.**
- There are only minor differences between the two delivered sets of combined solutions, which differ in terms of weighting strategy. Satellite-specific weighting is the official IGS product.

Future step 1: GPS and BeiDou satellites should be equipped with SLR retroreflectors and tracked by the SLR stations to provide information on orbit modeling issues.

Future step 2: Co-location in space onboard GNSS using space ties for future ITRF realizations.

Future step 3: Combined SLR+GNSS orbits.

GNSS+SLR combinations – removing systematic patterns



Bury G., Sośnica K., Zajdel R., Strugarek D., Hugentobler U. (2021)
Determination of precise Galileo orbits using combined GNSS and SLR observations. GPS Solutions, Vol. 25 No. 11,
URL: https://link.springer.com/article/10.1007/s10291-020-01045-3

Thank you for your attention

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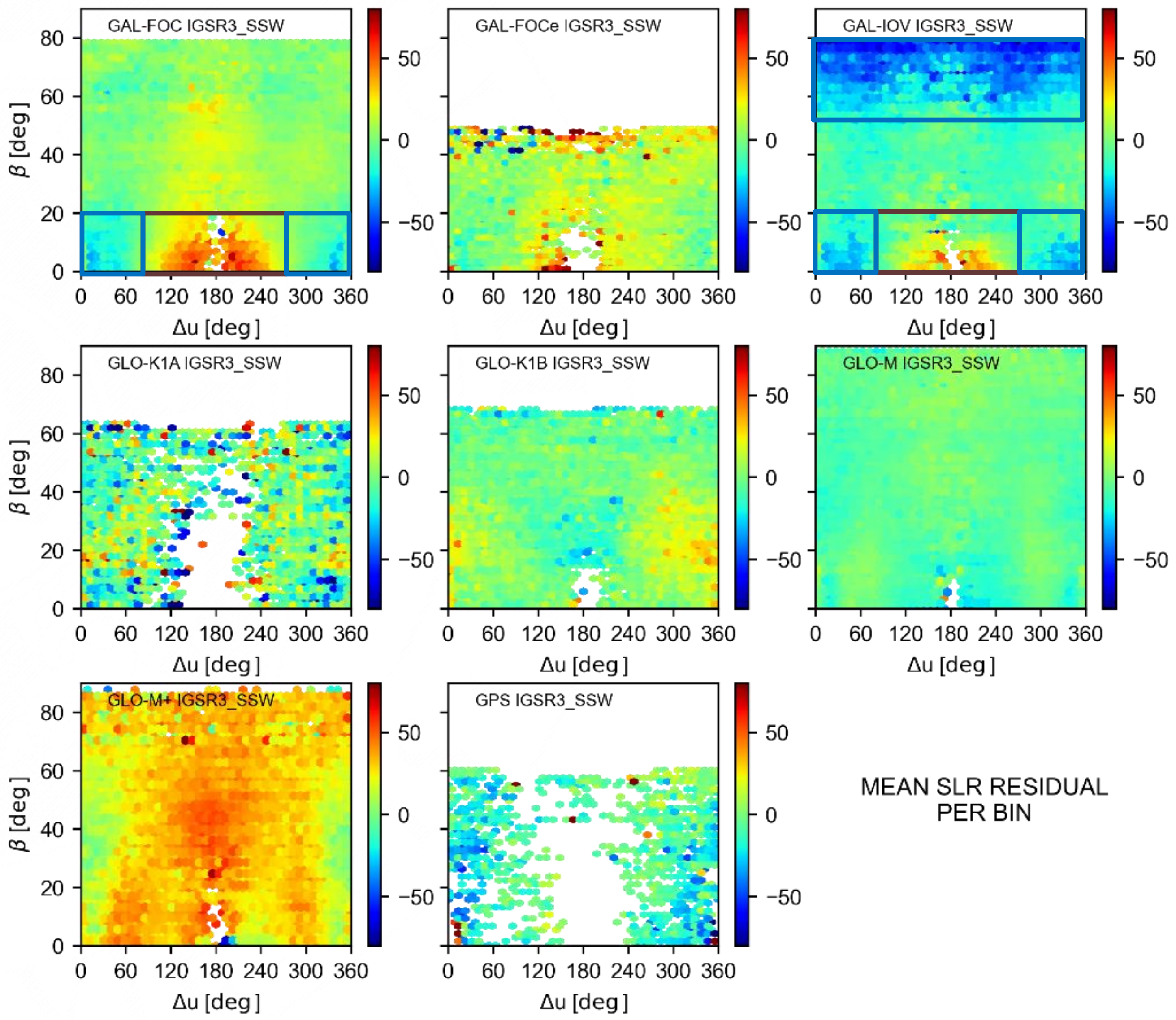
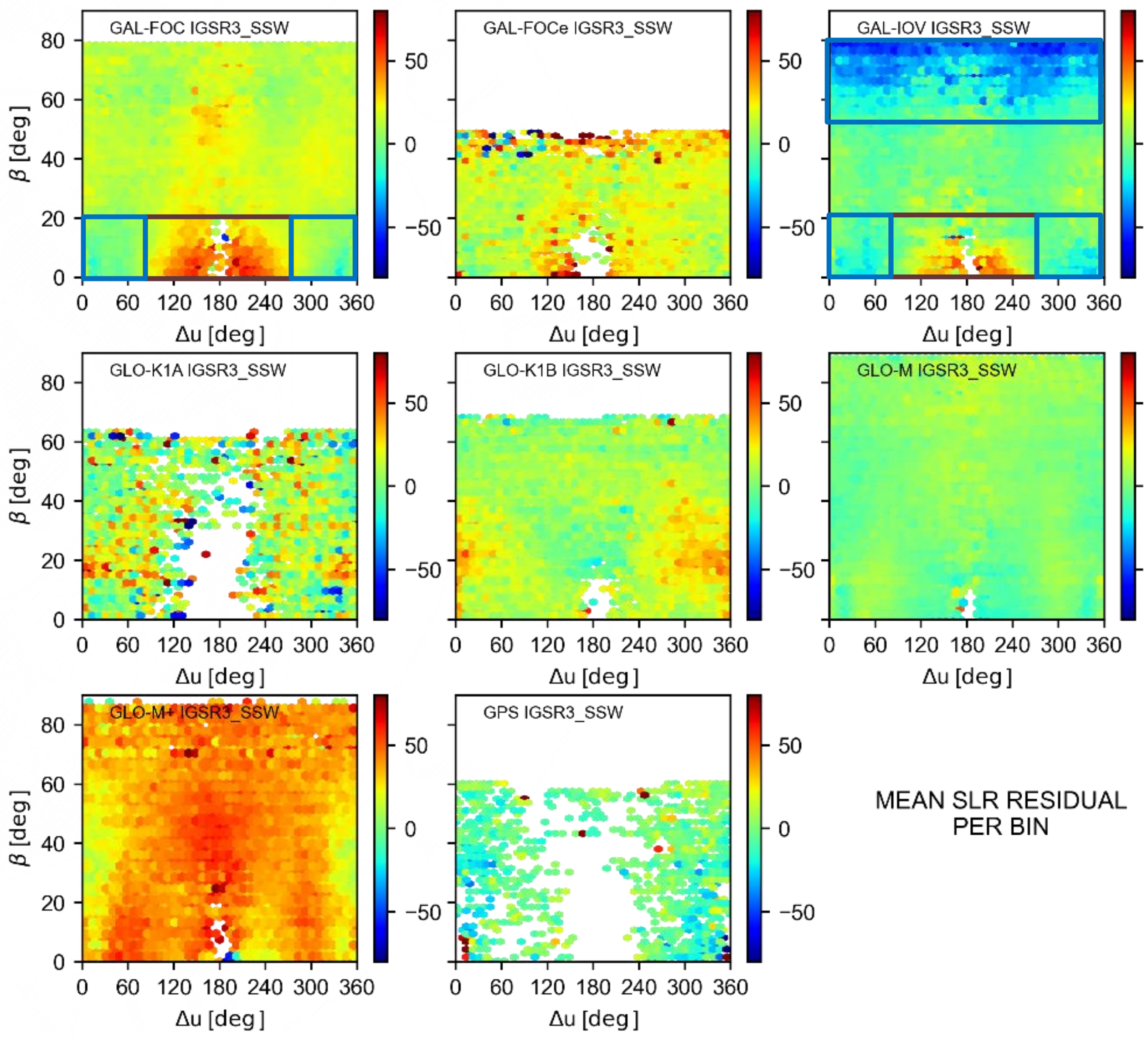
Orbit modeling issues – Differences after handling detector specific biases



MEAN SLR RESIDUAL PER BIN

BIASED

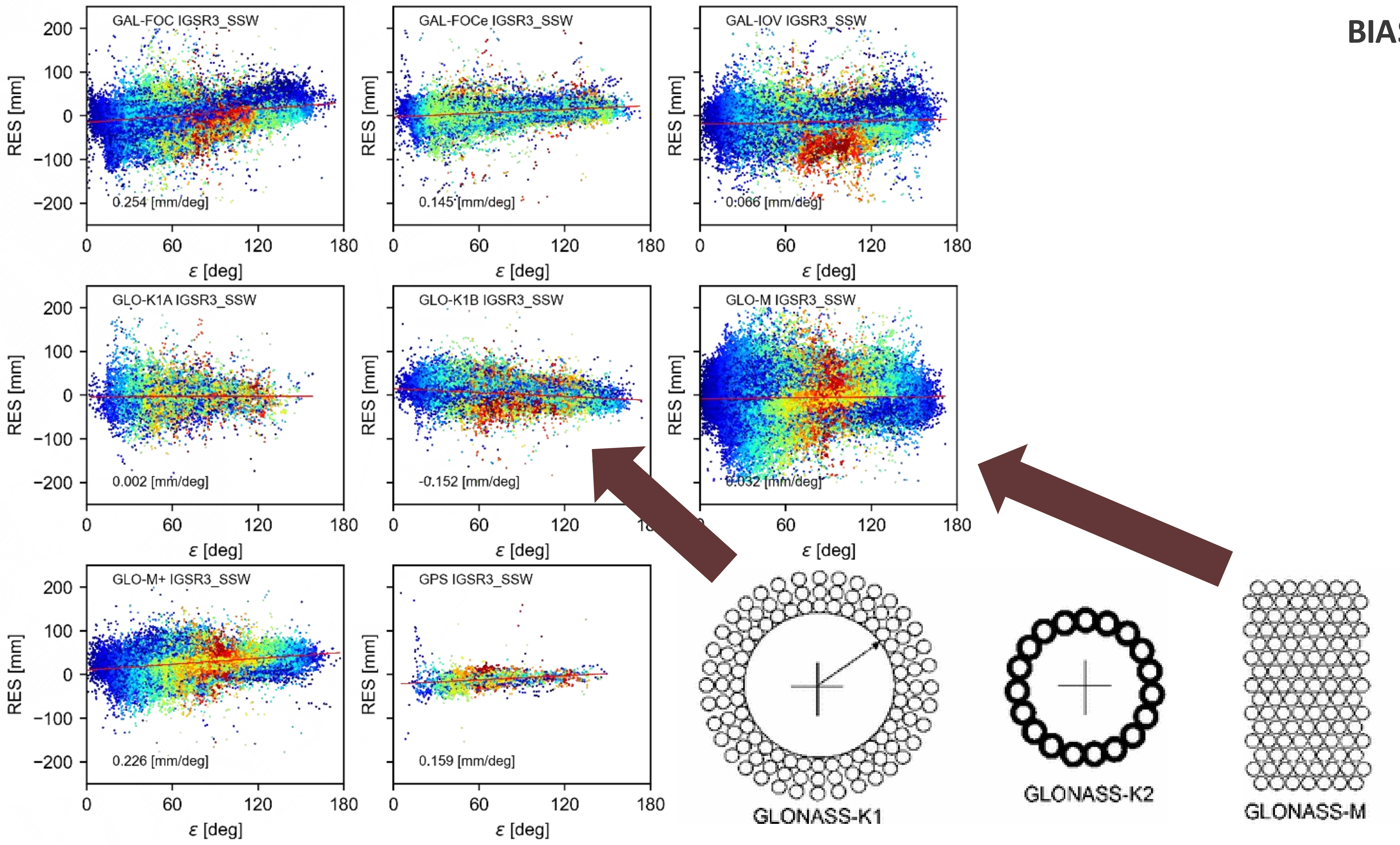
Orbit modeling issues – Differences after handling detector specific biases



NO DETECTOR BIAS

Orbit modeling issues – Differences after handling detector specific biases

BIASED



Orbit modeling issues – Differences after handling detector specific biases

NO DETECTOR BIAS