2023 VIRTUAL INTERNATIONAL WORKSHOP ON LASER RANGING
October 16-20, 2023
New Developments in Satellite Laser Ranging
ILRS

IGiG
Wrocław University of Environmental and Life Sciences

Extending ILRS support to 24 Beidou-3 satellites performance and outlook

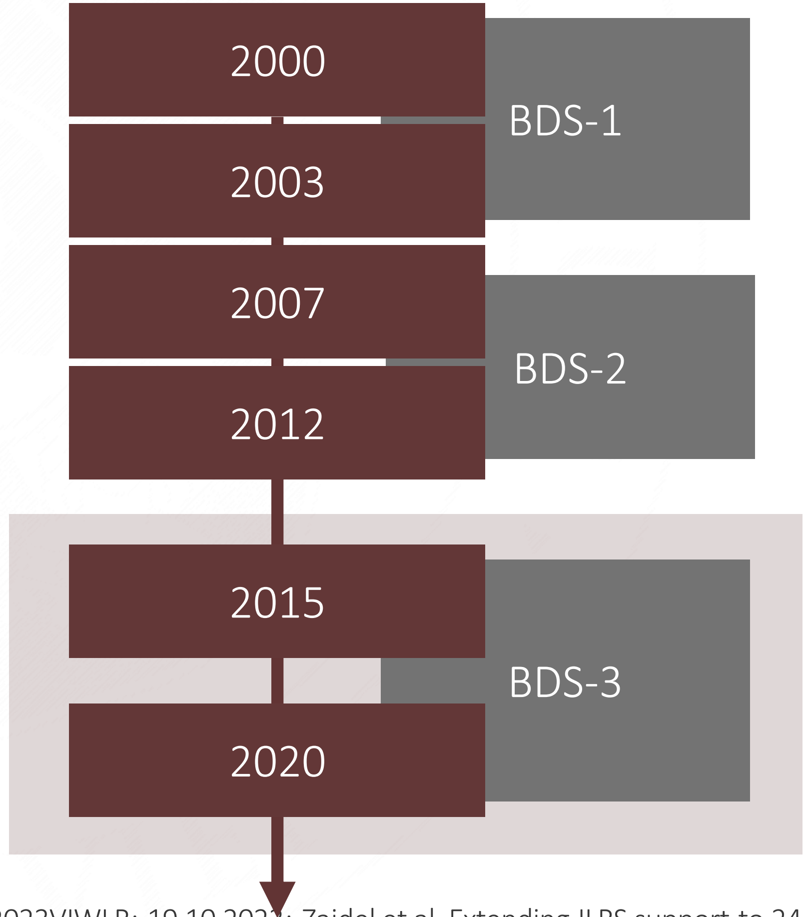
Radosław Zajdel, Adrian Nowak, Krzysztof Sośnica

Institute of Geodesy and Geoinformatics, UPWr, Wrocław, Poland

BDS-3 Tracking - Background

- In January 2023, **the ILRS approved tracking 20 additional Beidou-3 Medium Earth Orbit (BDS-3 MEO) satellites, instead of 4 (2 BDS-3 CAST and 2 BDS-3 SECM-A).**

3 GEO, 3 IGSO, and 24 MEO



14 satellites manufactured by Shanghai Engineering Center for Microsatellites (SECM) and 10 by China Academy of Space Technology (CAST).

- Within the SECM group of satellites, manufacturer informed us about two subtypes called SECM-A and -B satellites, which have different dimensions according to the China Satellite Navigation Office (CSNO) metadata file.
- Official metadata file specifies that there is only one type of the CAST satellites;
- Four CAST satellites are equipped with SAR antennas, i.e., C32/C33, C34/C35 (Li et al. 2021).

BDS-3 Tracking - Background

- The BDS constellation is **intriguing for the scientific and GNSS market community**.

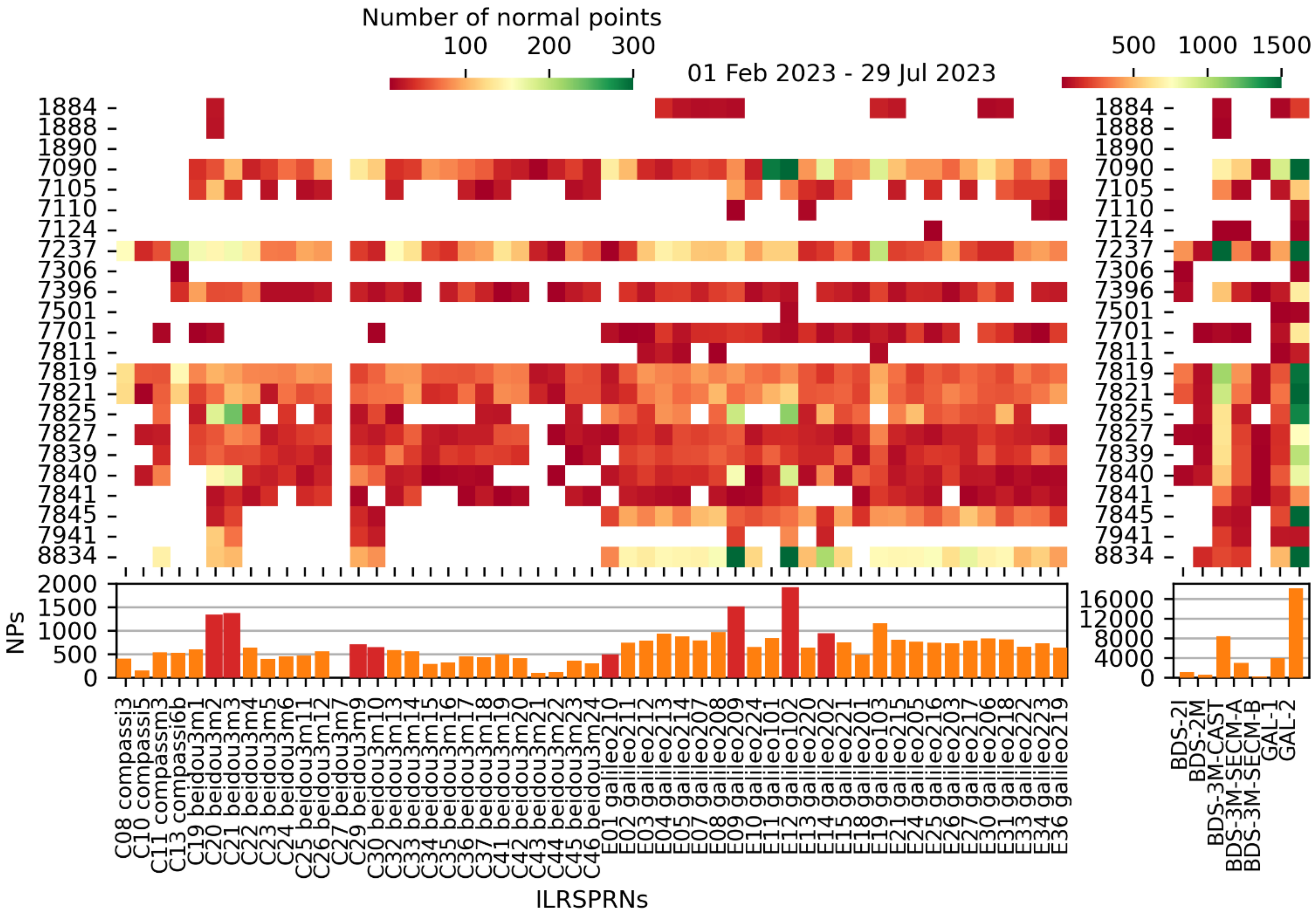
- The IGS community wishes to incorporate BDS into future releases of global terrestrial reference frames, **just as we did with Galileo for ITRF2020.**

- The previous analyses of the individual BDS-3 MEO satellites show that we may distinguish more groups of satellites than reported by CSNO, e.g., based on the patterns in the solar radiation pressure model parameters (e.g., Zajdel et al. 2022) or estimated phase center patterns (e.g., Huang et al. 2023)
    - Zajdel, R., Steigenberger, P. & Montenbruck, O. On the potential contribution of BeiDou-3 to the realization of the terrestrial reference frame scale. GPS Solut 26, 109 (2022). https://doi.org/10.1007/s10291-022-01298-0
    - Huang, C., Song, S., He, L. *et al.* Estimation of antenna phase center offsets for BDS-3 satellites with the metadata and receiver antenna calibrations. *J Geod* **97**, 57 (2023). https://doi.org/10.1007/s00190-023-01757-7

- **Because of that, Satellite Laser Ranging (SLR) data was crucially required for performing the so-called SLR orbit validation and enhance our understanding of the system, particularly regarding orbit modeling issues.**

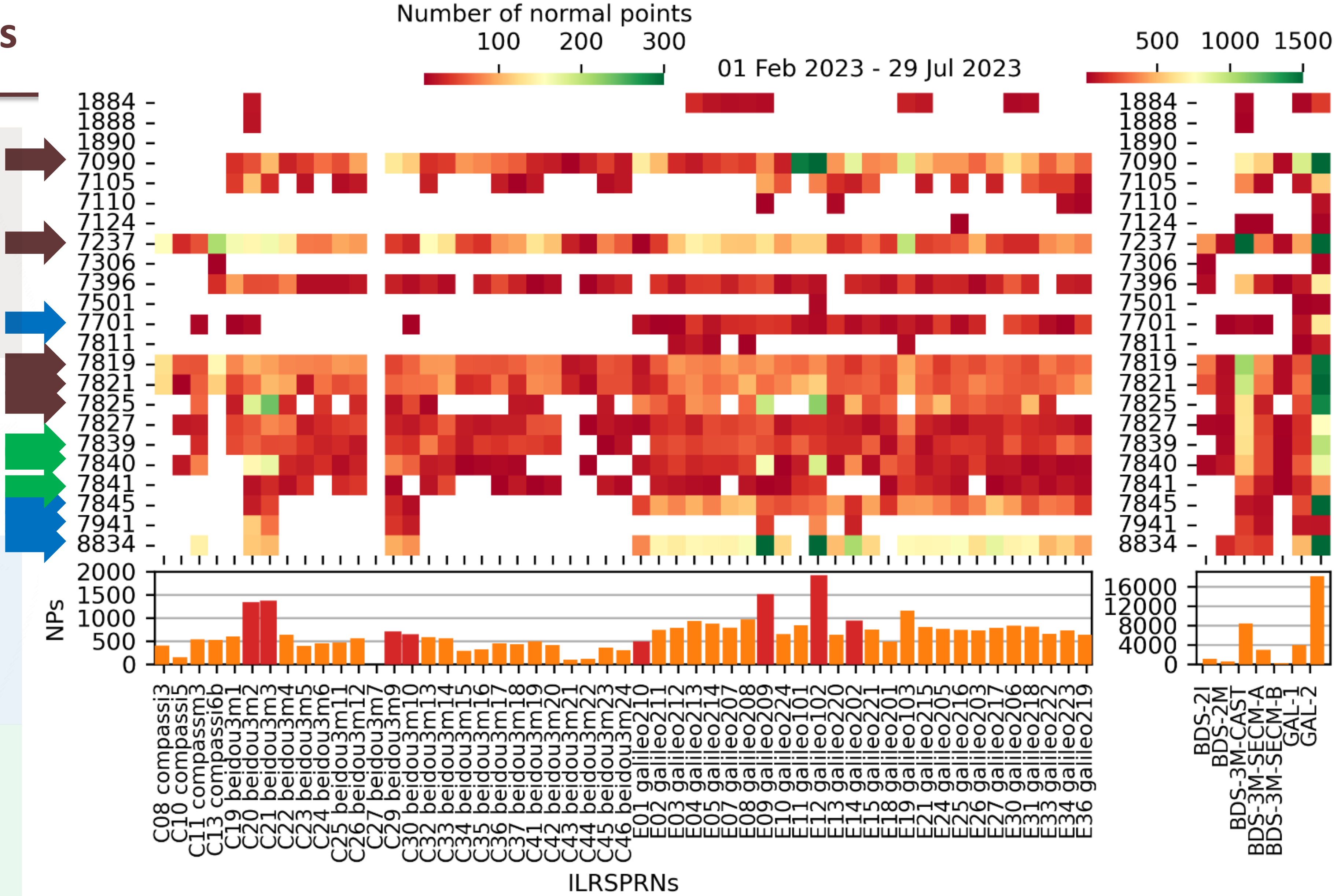
Number of observations

- Over the first 6 months, about 220 normal points per month were recorded for high-priority BDS-3 satellites, along with 75 for low-priority ones.
- Comparing the number of normal points for the BDS-3 and Galileo satellites, the stations provide almost two times more observations for Galileo than for the BDS-3 satellites for the non ILRS priority satellites.

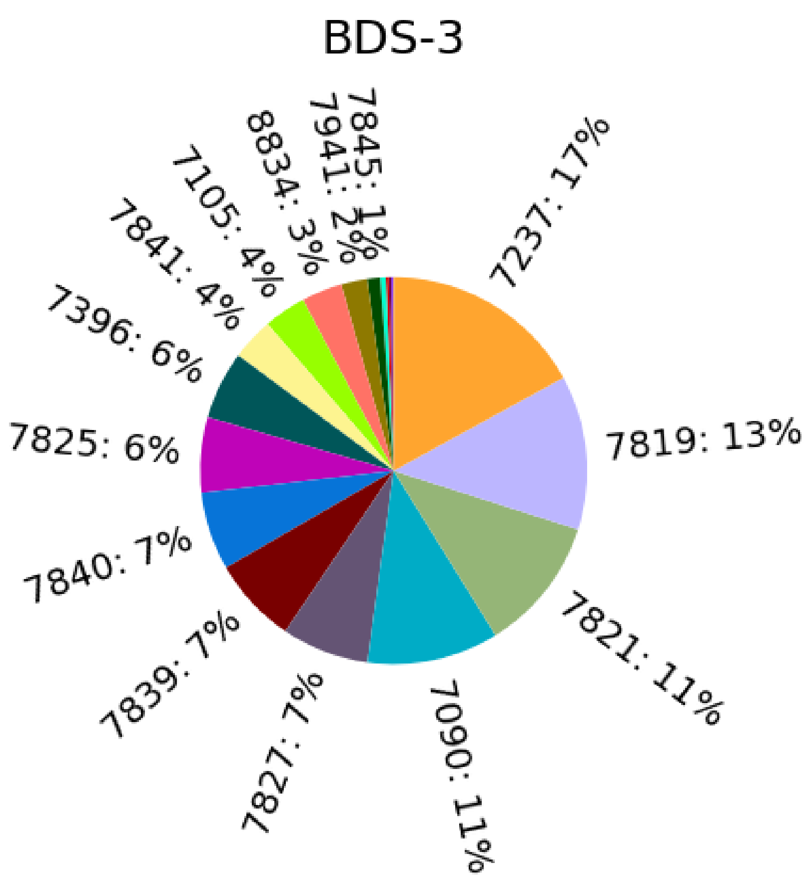


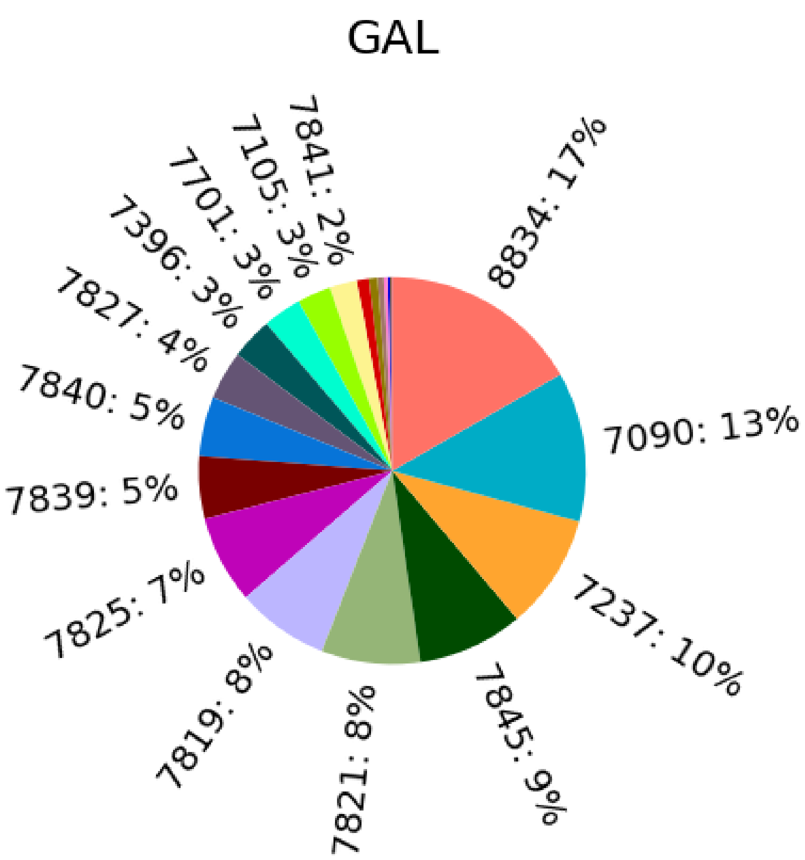
Number of observations

- The Chinese and Australian stations namely, **7819, 7821, 7237, 7825, and 7090**, demonstrate high productivity by tracking all potential GNSS targets.
- The European stations are divided into two groups.
  - Both groups focus on the domestic Galileo constellation.
  - However, for other systems such as BDS, stations **7845, 7941, and 8834** exclusively observe high-priority satellites.
  - In the second group, stations **7839, 7840, and 7841** also support the remaining satellites, albeit with lower intensity.



Tracking BDS-3 – contributing stations

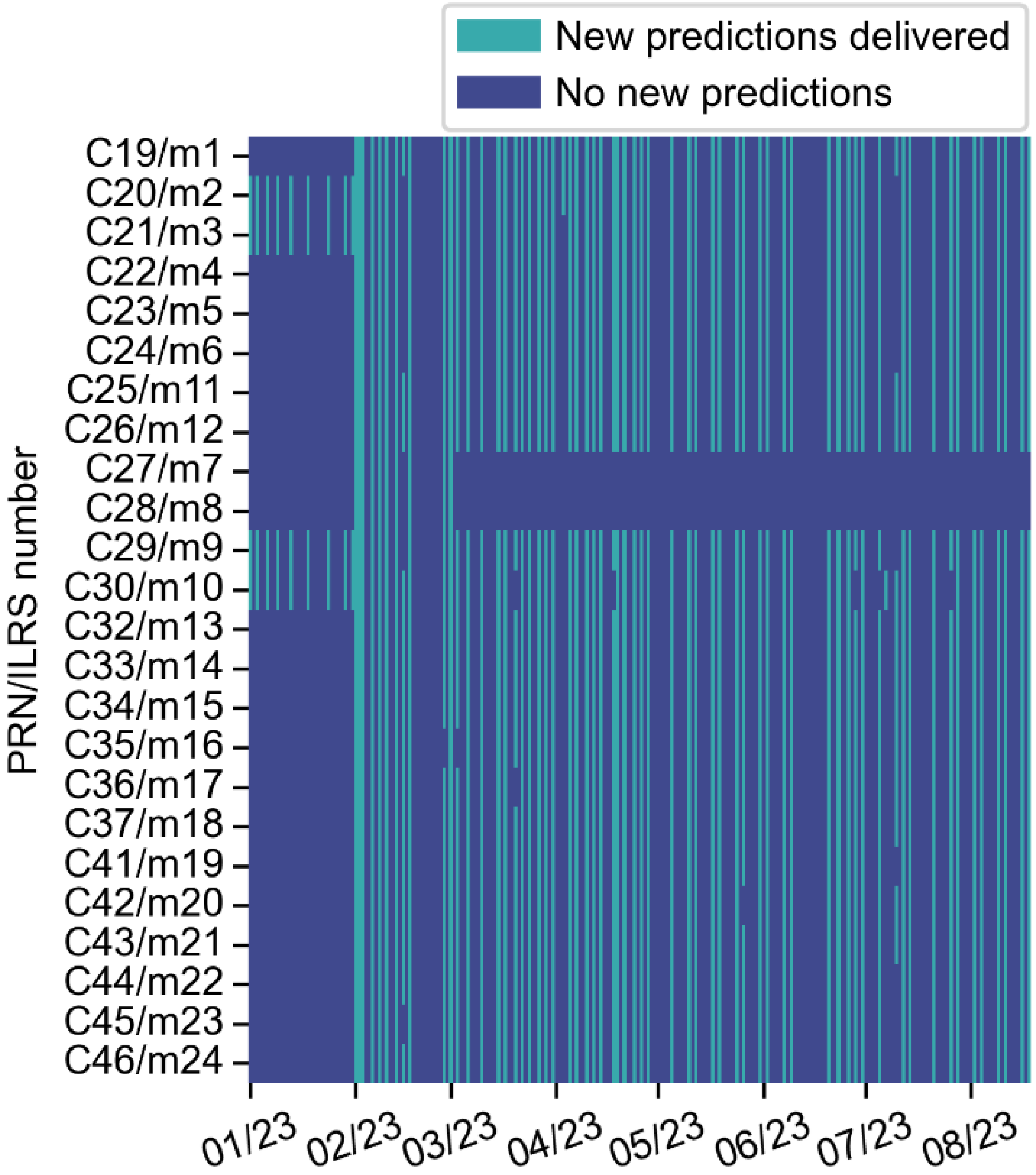




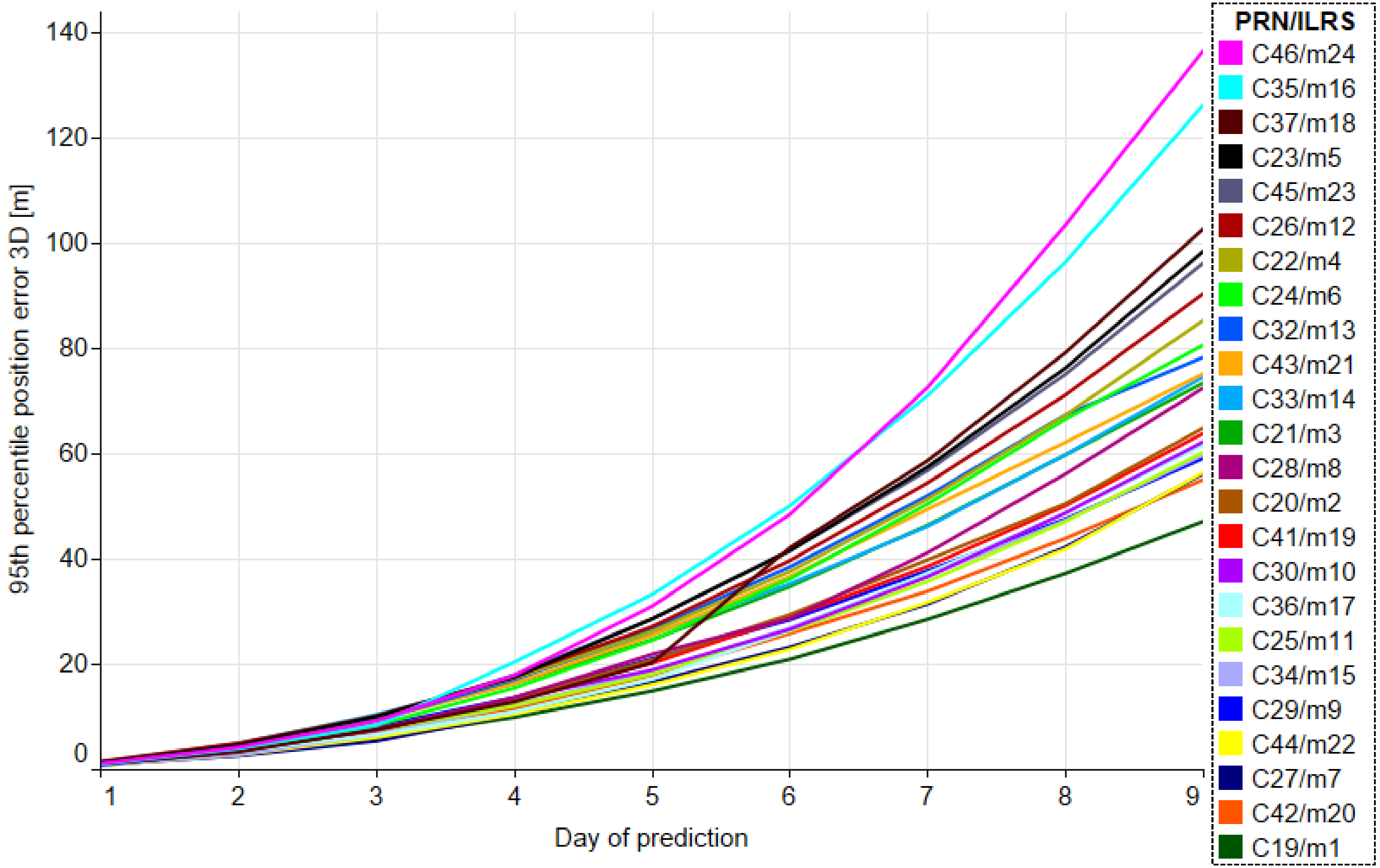
- Over half of the normal points to BDS-3 MEO satellites were contributed by five out of the 24 active laser stations: **7237 (Changchun, 17%), 7819 (Beijing, 13%), 7821 (Shanghai, 11%), 7090 (Yarragadee, 11%), and 7827 (SOS Wettzell, 7%).**
- During the same period, the Galileo constellation was predominantly supported by another set of five stations: **8834 (Wettzell, 17%), 7090 (Yarragadee, 13%), 7237 (Changchun, 10%), 7845 (Grasse, 9%), and 7821 (Shanghai, 8%).**
- This indicates a discernible prioritization of ILRS stations.

Orbit predictions

- The average time between successive releases of these new satellite prediction files is approximately **3 days, with occasional intervals of 5 to 10 days.** SHA's orbit predictions extend for 9 consecutive days following each release.
- When considering the availability of new prediction files, data from consecutive days, specifically 5-9 days, must also be employed by station operators.
- SHA stopped providing predictions for BeiDou-3M7 (C27) and BeiDou-3M8 (C28) at the beginning of March.



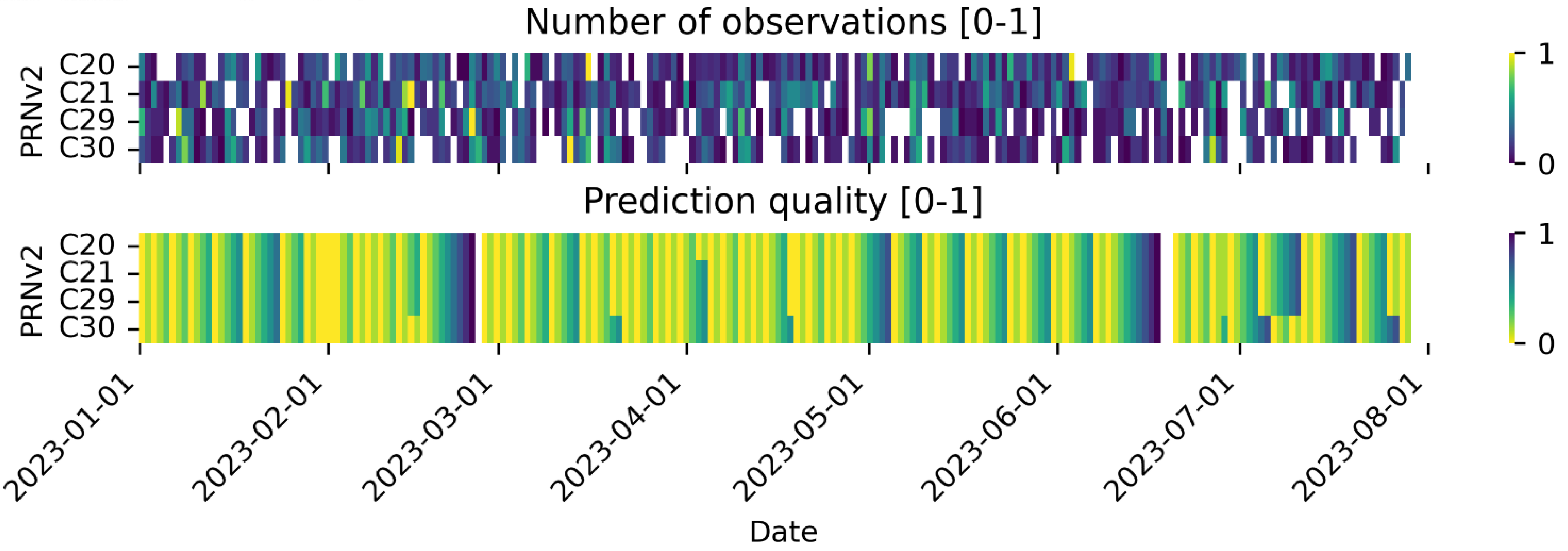
Orbit prediction quality



- The 95th percentile of the predicted satellite position 3D error varies among individual satellites, measuring between
- <3 m → 1st day
- 10 to 25 m → 5th day
- 42 to 140 m → 9th day

- The number of BDS observations is 2 times less than for Galileo, but is the lower prediction quality a reason for stations to collect fewer observations?

Orbit prediction quality vs. Number of Normal Points

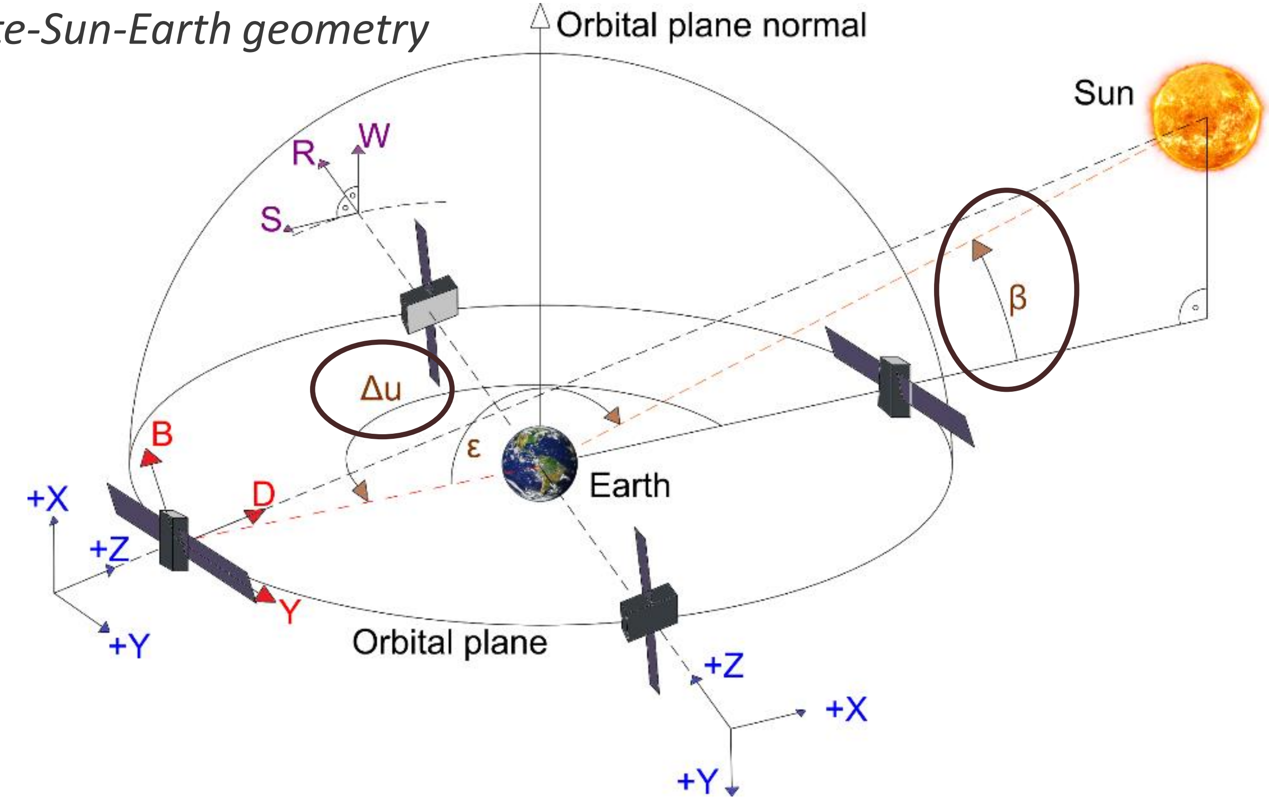


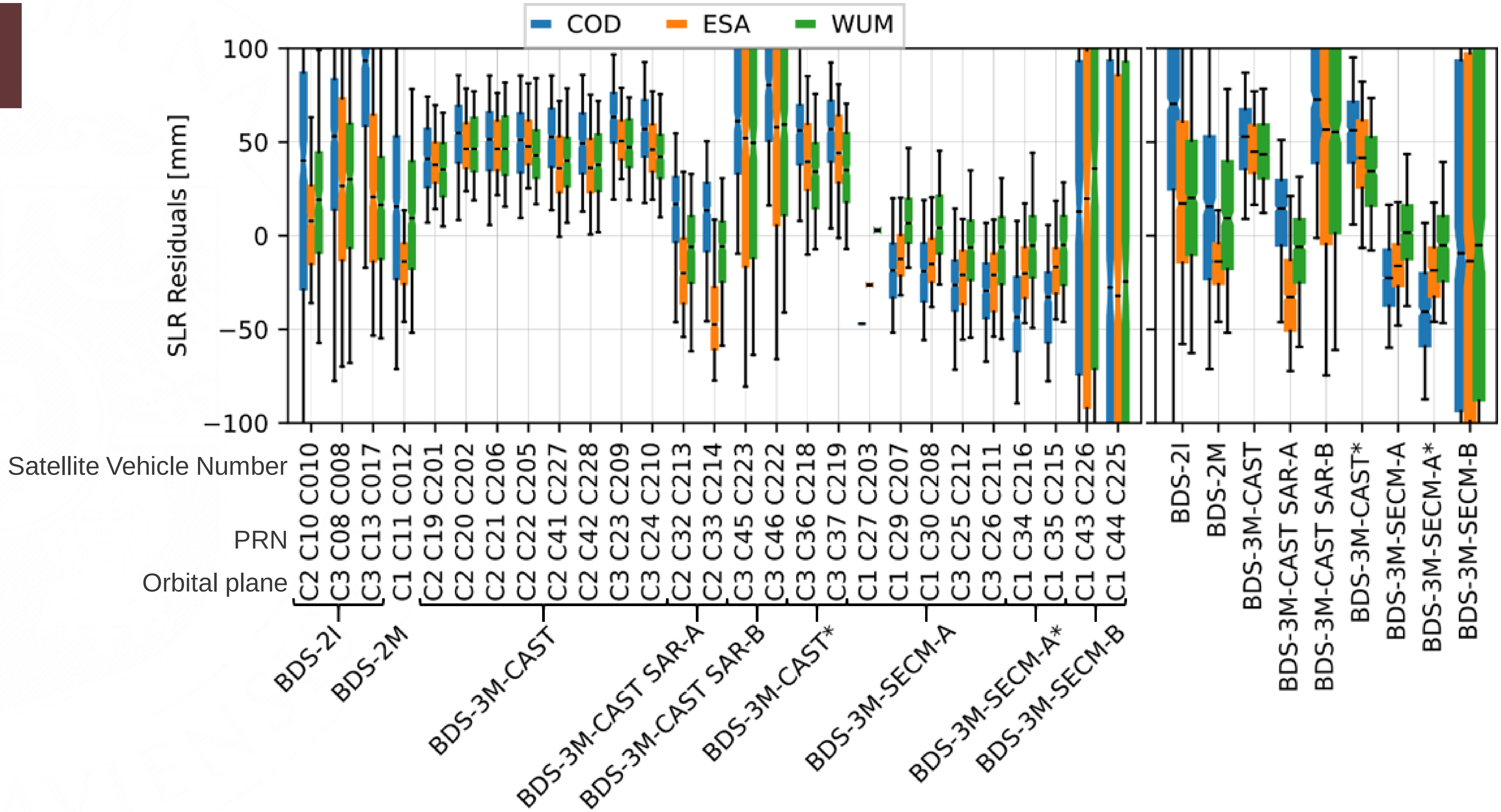
- No correlation between the prediction quality and the numer of observations, which means that the prediction quality is enough. Even if the predictions are not delivered, the satellites are tracked. As we assumed, the stations may make use of Two-Line Element for inhouse orbit predictions instead of using CPF predictions.

SLR Validation

- Precise orbits delivered by:
  Center for Orbit Determination in Europe (COD)
  European Space Agency (ESA)
  Wuhan University (WUM)
- Stations: SLRF2020, FES2014b
- Satellites: most of the background models consistent with the validated orbits
  mm level orbit reconstruction
- Software: Bernese GNSS Software 5.4

satellite-Sun-Earth geometry




COD
ESA
WUM
SLR Residuals [mm]
100
50
0
−50
−100
Satellite Vehicle Number
PRN
Orbital plane
C010 C008 C017 C012 C201 C202 C206 C205 C227 C228 C209 C210 C213 C214 C223 C222 C218 C219 C203 C207 C208 C212 C211 C216 C215 C226 C225
C10 C08 C13 C11 C19 C20 C21 C22 C41 C42 C23 C24 C32 C33 C45 C46 C36 C37 C27 C29 C30 C25 C26 C34 C35 C43 C44
C2 C3 C3 C1 C2 C2 C2 C2 C2 C2 C3 C3 C2 C2 C3 C3 C3 C3 C1 C1 C1 C3 C3 C1 C1 C1 C1
BDS-2I
BDS-2M
BDS-3M-CAST
BDS-3M-CAST SAR-A
BDS-3M-CAST SAR-B
BDS-3M-CAST*
BDS-3M-SECM-A
BDS-3M-SECM-A*
BDS-3M-SECM-B

Station-specific statistics

detname	MEAN OFFSET BDS-3M-CAST	MEAN OFFSET BDS-3M-SECM-A	MEAN OFFSET GAL-2	STD OF SLR RESIDUALS BDS-3M-CAST	STD OF SLR RESIDUALS BDS-3M-SECM-A	STD OF SLR RESIDUALS GAL-2
GR_1 CSPAD 7701 2%	57.8	10.7	17.0	17.6	13.6	11.8
GR_1 CSPAD 7825 7%	64.7	-6.6	9.3	12.8	10.6	11.3
GR_1 CSPAD 7827 4%	36.8	-22.8	9.0	15.6	21.6	12.7
GR_1 CSPAD 7839 5%	44.0	-13.4	10.6	13.3	13.9	11.5
GR_1 CSPAD 7840 5%	39.2	-17.8	2.3	11.4	14.1	12.1
GR_2 MCP 7105 2%	40.4	-27.4	7.1	13.2	15.2	13.6
GR_2 MCP 7110 0%	28.4		-4.6	4.9		8.7
GR_2 MCP 7941 1%	31.1	-26.6	-7.7	11.5	8.1	13.1
GR_2 PMT 7501 0%			3.3			10.5
GR_3 CSPAD 7841 2%	40.6	-28.3	7.9	11.6	16.4	16.4
GR_3 CSPAD 7845 6%	31.5	-22.2	-2.3	7.1	9.2	11.9
GR_3 MCP 7090 12%	36.1	-30.2	-12.0	13.4	14.0	11.3
GR_3 MCP 8834 10%	39.4	-12.6	6.9	8.5	9.4	11.3
GR_4 SPAD * 7237 14%	56.9	4.5	26.4	17.6	16.3	13.4
GR_4 CSPAD* 7249 0%	-5.0	-54.9	-40.9	3.5	11.4	10.2
GR_4 CSPAD* 7819 10%	52.2	-6.6	22.4	22.0	20.5	20.1
GR_4 CSPAD* 7821 11%	32.7	-19.1	0.0	17.6	13.5	13.7
GR_5 MCP 7124 0%	26.6	-51.3	-18.4	2.2	8.0	7.3
GR_5 PMT 1884 1%	15.7		-14.4	6.1		14.0
GR_5 PMT 1888 0%	40.5	-16.3		10.9	4.8	
GR_5 PMT 1890 0%	34.1			16.1		
GR_5 PMT 7811 0%			-29.8			88.8

- The station grouping arises from the analysis of handling detector-specific issues in SLR validation of GNSS orbits

Zajdel, R., Masoumi, S., Sośnica, K. et al. Combination and SLR validation of IGS Repro3 orbits for ITRF2020. J Geod 97, 87 (2023). https://doi.org/10.1007/s00190-023-01777-3

Station-specific statistics

detname	MEAN OFFSET BDS-3M-CAST	MEAN OFFSET BDS-3M-SECM-A	MEAN OFFSET GAL-2	STD OF SLR RESIDUALS BDS-3M-CAST	STD OF SLR RESIDUALS BDS-3M-SECM-A	STD OF SLR RESIDUALS GAL-2
GR_1 CSPAD 7701 2%	57.8	10.7	17.0	17.6	13.6	11.8
GR_1 CSPAD 7825 7%	64.7	-6.6	9.3	12.8	10.6	11.3
GR_1 CSPAD 7827 4%	36.8	-22.8	9.0	15.6	21.6	12.7
GR_1 CSPAD 7839 5%	44.0	-13.4	10.6	13.3	13.9	11.5
GR_1 CSPAD 7840 5%	39.2	-17.8	2.3	11.4	14.1	12.1
GR_2 MCP 7105 2%	40.4	-27.4	7.1	13.2	15.2	13.6
GR_2 MCP 7110 0%	28.4		-4.6	4.9		8.7
GR_2 MCP 7941 1%	31.1	-26.6	-7.7	11.5	8.1	13.1
GR_2 PMT 7501 0%			3.3			10.5
GR_3 CSPAD 7841 2%	40.6	-28.3	7.9	11.6	16.4	16.4
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GR_5 PMT 1884 1%	15.7		-14.4	6.1		14.0
GR_5 PMT 1888 0%	40.5	-16.3		10.9	4.8	
GR_5 PMT 1890 0%	34.1			16.1		
GR_5 PMT 7811 0%			-29.8			88.8

- One of the major issues with the consistency of SLR to GNSS data is the different mean offset of residuals for different stations/groups of stations.

Station-specific statistics

detname	BDS-3M-CAST	BDS-3M-SECM-A	GAL-2	BDS-3M-CAST	BDS-3M-SECM-A	GAL-2
GR_1 CSPAD 7701 2%	57.8	10.7	17.0	17.6	13.6	11.8
GR_1 CSPAD 7825 7%	64.7	-6.6	9.3	12.8	10.6	11.3
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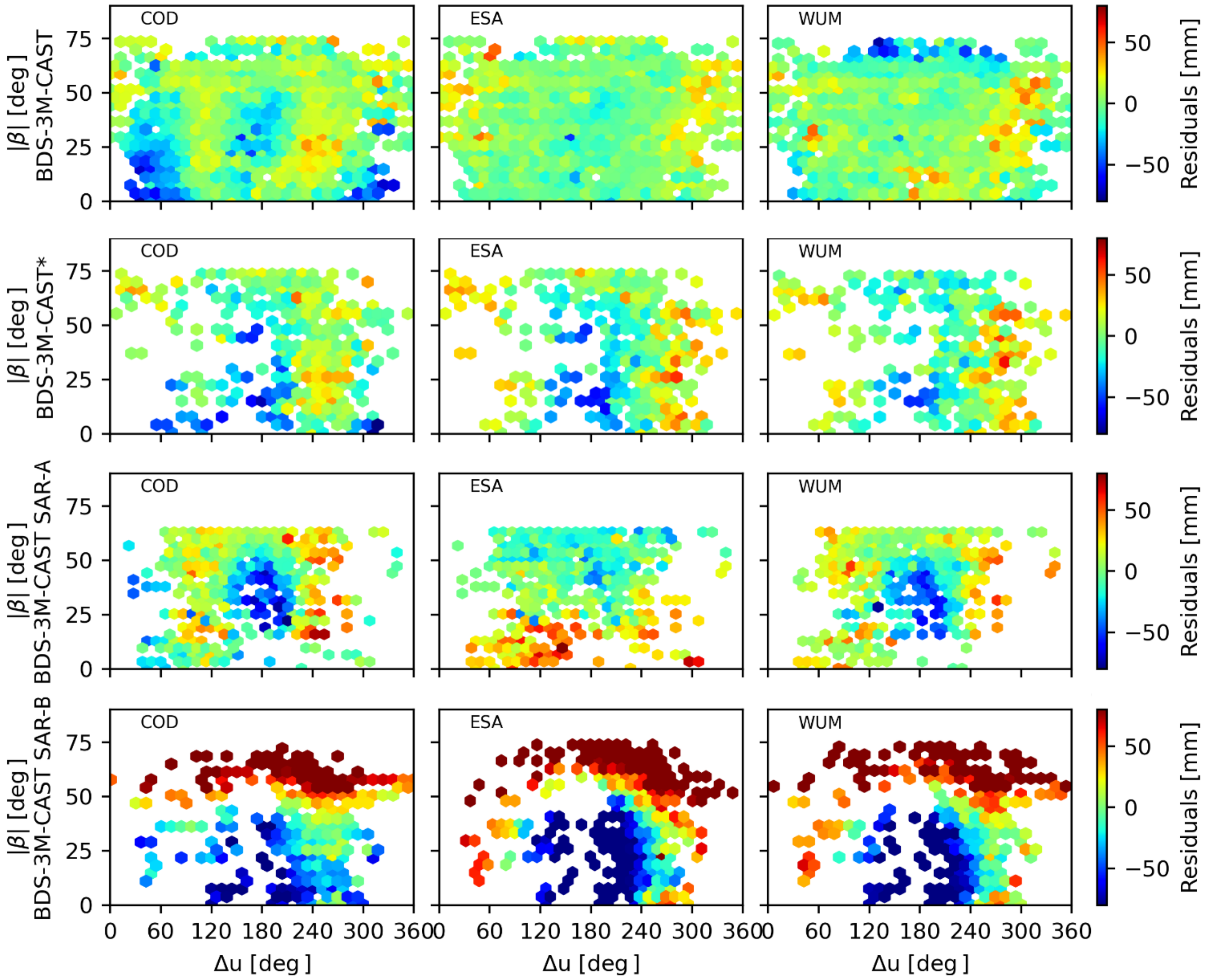
GR_5 PMT 1890 0%	34.1			16.1		
GR_5 PMT 7811 0%			-29.8			88.8

- STD of SLR residuals reaches even **7-8 mm (7845, 8834) but also 10-13 mm for productive stations (7090,7840)**
- **When we take all stations as a whole, the STD is of the order of 18-25 mm.**

SLR Validation

- SLR validation of individual satellites has revealed that the BDS-3 MEO constellation comprises more satellite groups than initially documented.
- In addition to the officially defined satellite groups such as BDS-3M-CAST, BDS-3M-SECM-A, and BDS-3M-SECM-B, four additional pairs of satellites with different SLR residual characteristics can be identified.
- The current orbit modeling approaches used by the ACs appear to work well for BDS-3M-CAST and BDS-3M-SECM satellites (12-24 satellites).



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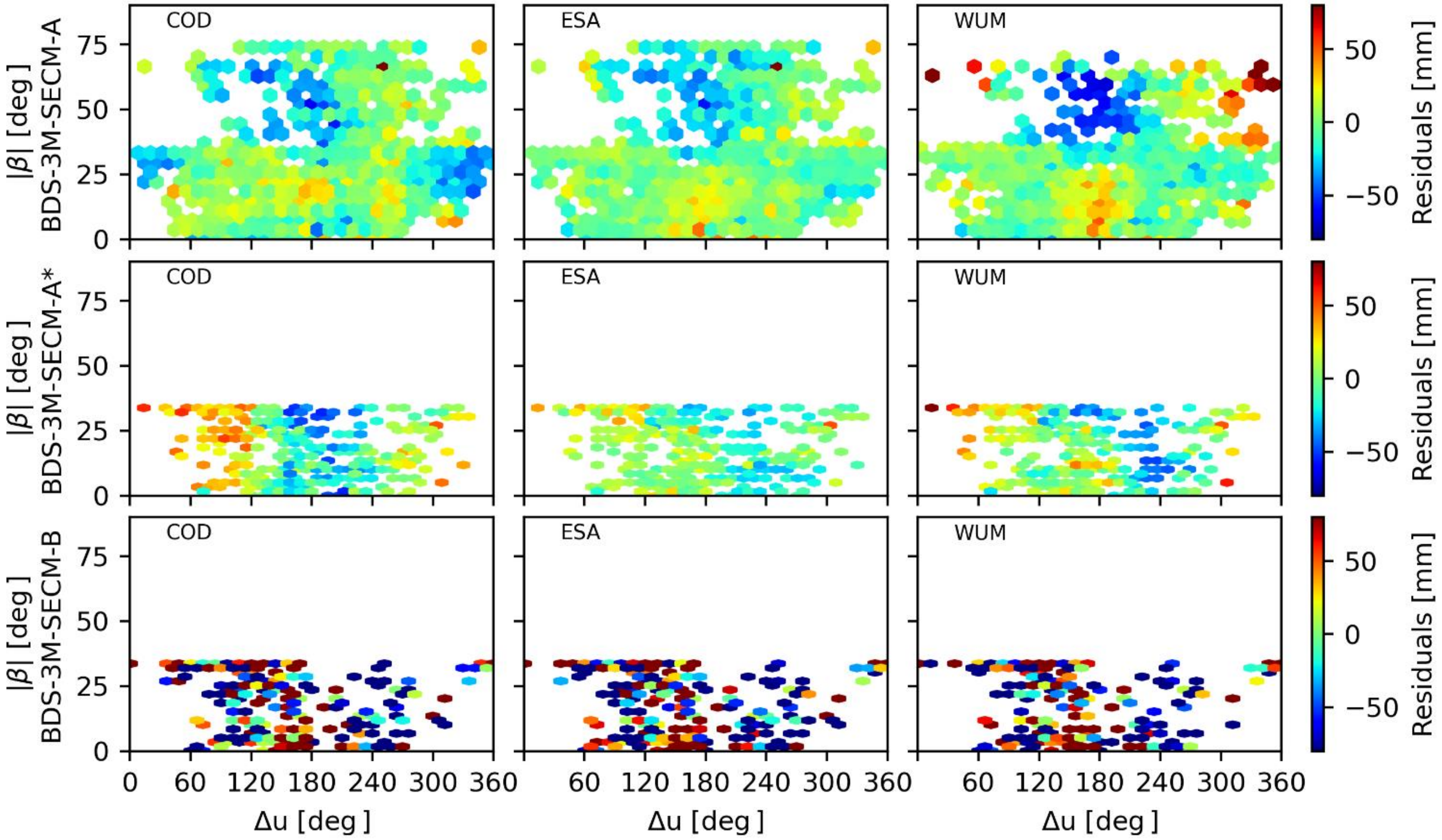


Conclusions

- The results highlight **the successful fulfillment of the ILRS network's request to track the entire BDS-3 constellation.**
- The stations provided nearly twice as many observations for Galileo satellites compared to BDS-3 satellites.
- As of March 2023, due to the suspension of **orbit prediction provision for the BeiDou-3M7 (C27) and M8 (C28) satellites, the ILRS network observes 22 BDS-3 satellites instead of the full 24.** This, however, may change if other sources start providing predictions for these satellites.
- SLR validation of individual satellites has revealed that the BDS-3 MEO constellation comprises more satellite groups than initially documented in the official metadata files distributed by BDS system operators.
  The results also point to some potential errors in the metadata associated with the LRA (M21 C43/M22 C44).
- The current orbit modeling approaches used by the ACs appear to work well for BDS-3M-CAST and BDS-3M-SECM satellites. However, this applies only to 12 out of the 24 satellites in the BDS-3 MEO constellation. Therefore, improving orbit modeling for the remaining satellites remains a challenge for the GNSS community.
- **Continued support from the ILRS network in finding inconsistencies in LRA offsets and providing increased numer of observations for satellites that require special attention is recommended to facilitate this task:**
  ?? Current ILRS recommendation: **C20/C21 (CAST), C29/C30 (SECM)**
  → <u>C20 (CAST) C29 (SECM-A) C32 (CAST SAR-A) C34 (CAST SAR-A*) C45 (CAST SAR-B) C36 (CAST*) C43 (SECM-B)</u>

Wrocław University of Environmental and Life Sciences

Thank you for your attention

Radosław Zajdel
radoslaw.zajdel@upwr.edu.pl

ORCID Connecting Research and Researchers

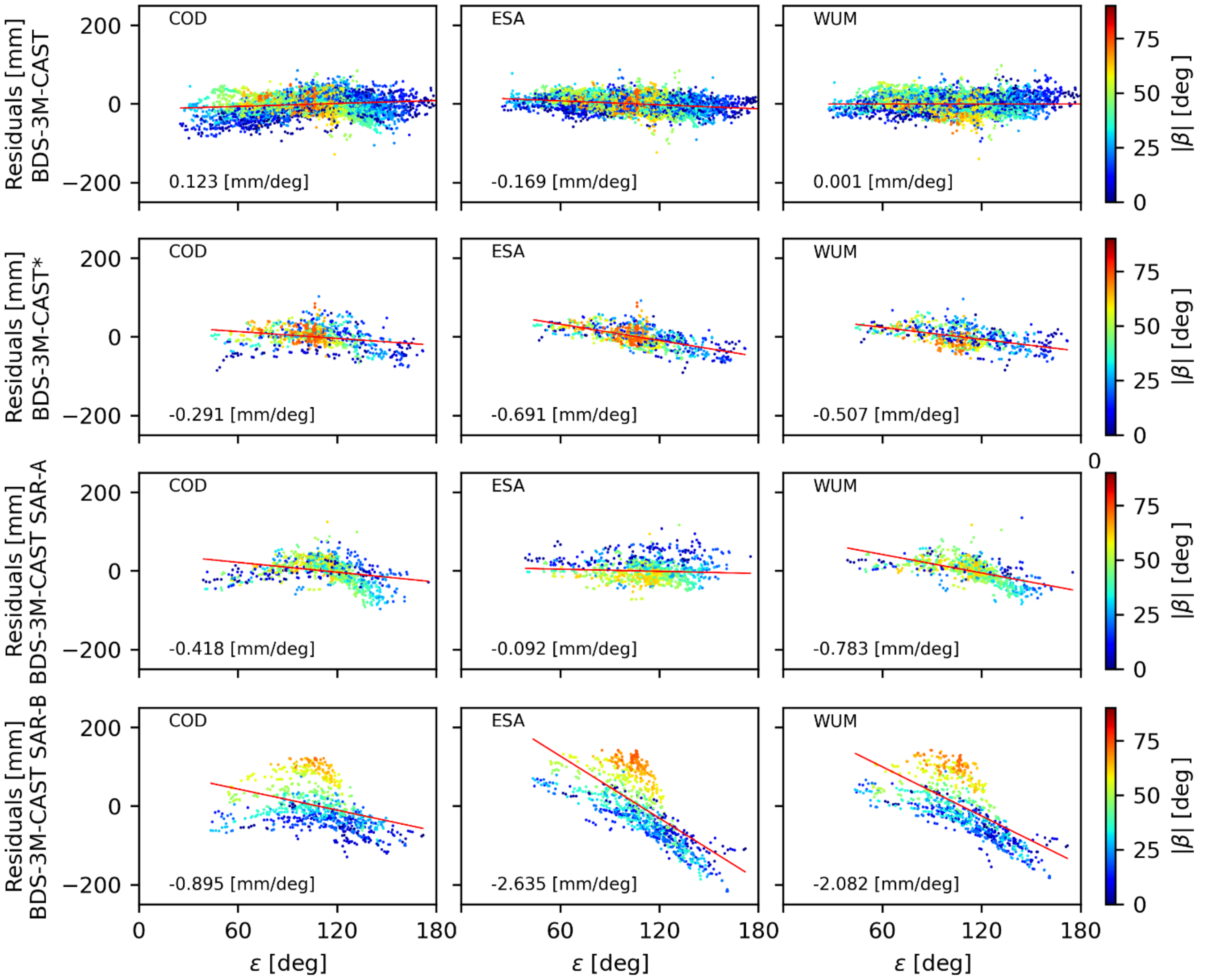
http://orcid.org/0000-0002-1634-388X

ResearchGate

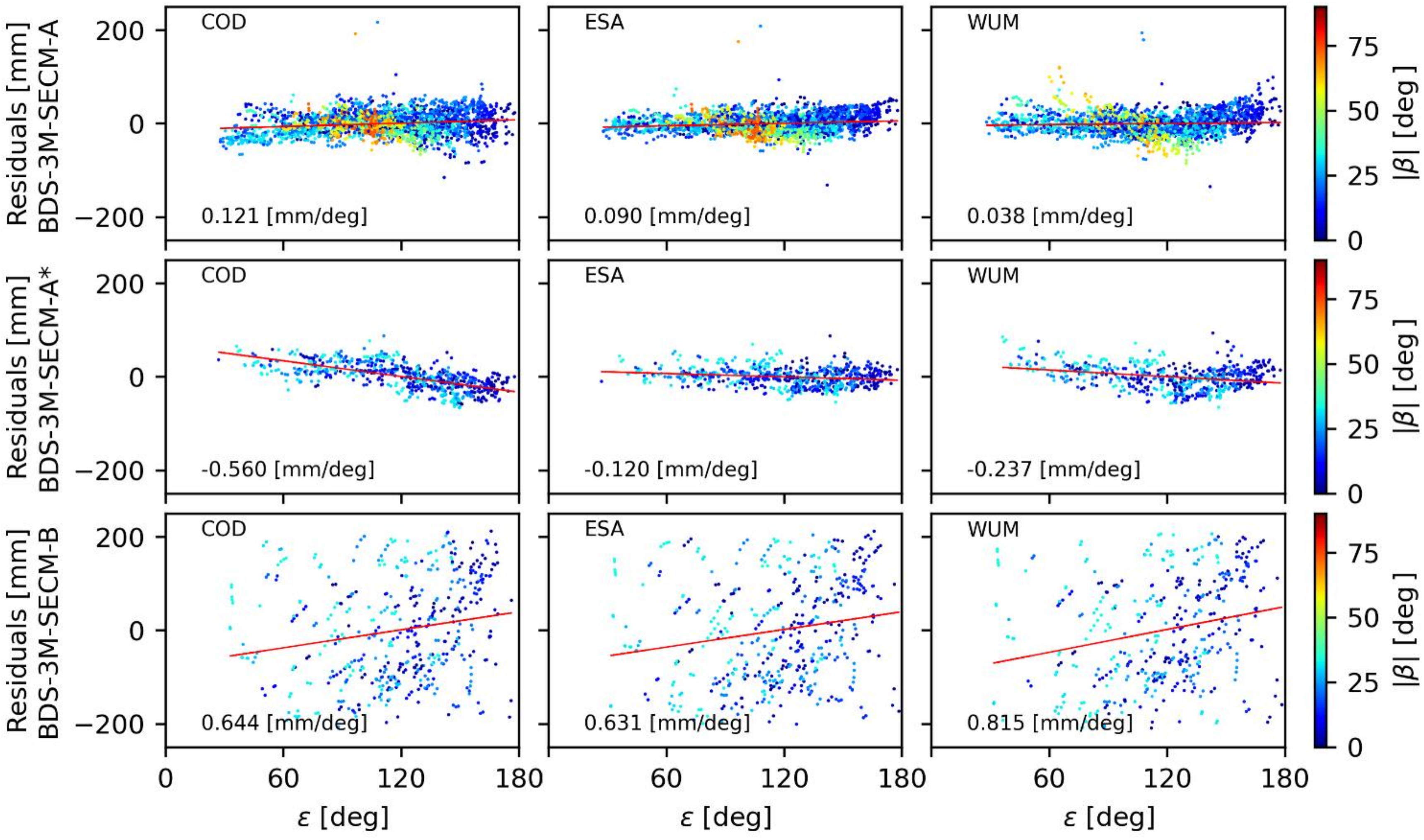
https://www.researchgate.net/profile/Radoslaw-Zajdel-2

Springer

Zajdel R., Nowak A., Sośnica K. et al. (2023) Satellite Laser Ranging to Beidou-3 Satellites – Initial Performance and Contribution to Improving Orbit Modeling. *GPS Solutions*. Under Review.



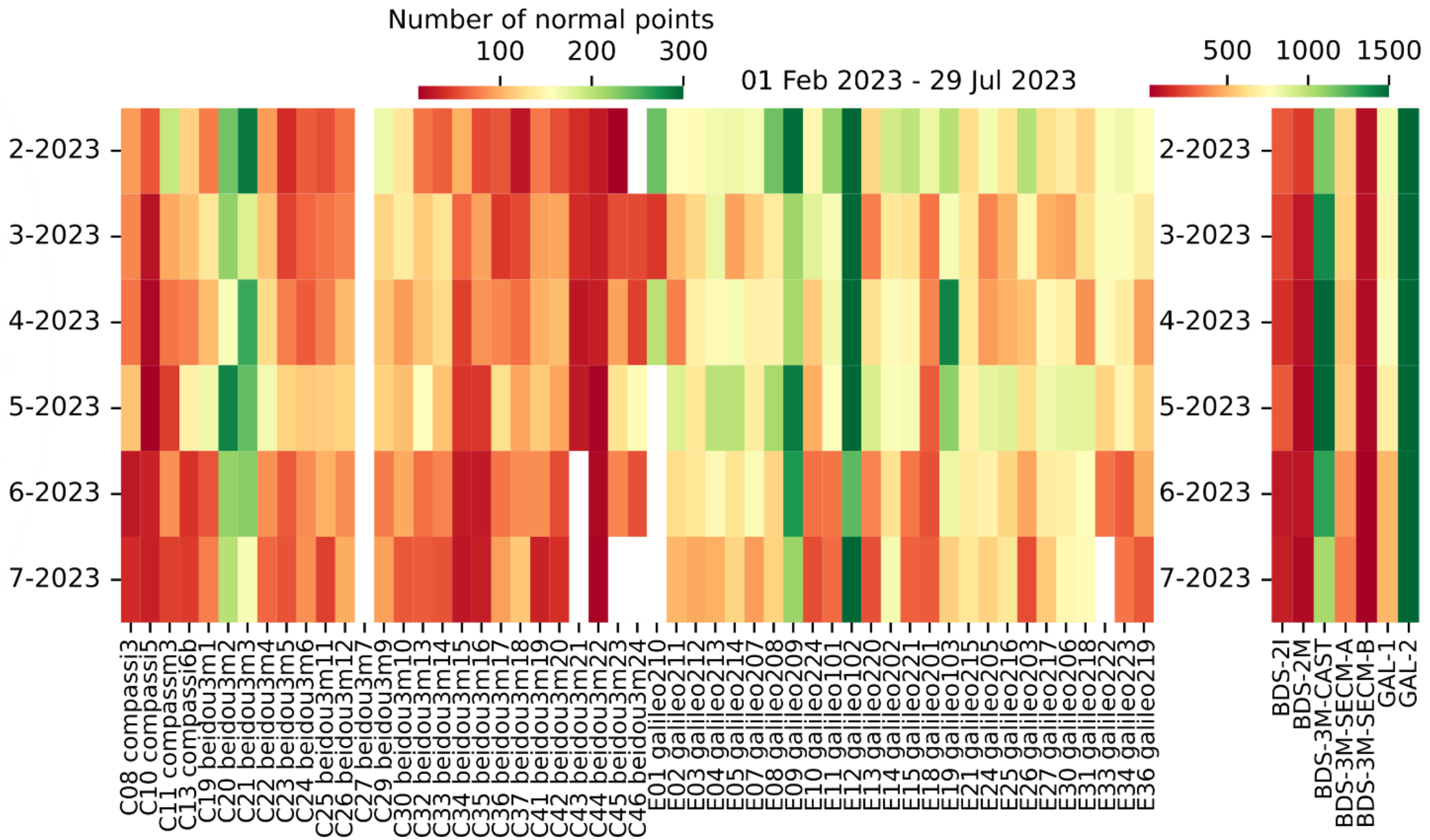
Residuals [mm] BDS-3M-CAST
Residuals [mm] BDS-3M-CAST*
Residuals [mm] BDS-3M-CAST SAR-A
Residuals [mm] BDS-3M-CAST SAR-B
COD
ESA
WUM
0.123 [mm/deg]
-0.169 [mm/deg]
0.001 [mm/deg]
-0.291 [mm/deg]
-0.691 [mm/deg]
-0.507 [mm/deg]
-0.418 [mm/deg]
-0.092 [mm/deg]
-0.783 [mm/deg]
-0.895 [mm/deg]
-2.635 [mm/deg]
-2.082 [mm/deg]
200
0
−200
0
60
120
180
ε [deg]
|β| [deg]
0
25
50
75


COD
ESA
WUM
0.121 [mm/deg]
0.090 [mm/deg]
0.038 [mm/deg]
-0.560 [mm/deg]
-0.120 [mm/deg]
-0.237 [mm/deg]
0.644 [mm/deg]
0.631 [mm/deg]
0.815 [mm/deg]
Residuals [mm] BDS-3M-SECM-A
Residuals [mm] BDS-3M-SECM-A*
Residuals [mm] BDS-3M-SECM-B
ε [deg]
|β| [deg]

ILRS Name	BDS-SVN	NORAD ID	COSPAR	SVN	PRN	Launch Date	Type	Type (ext)
beidou3m1	MEO-1	43001	2017-069A	C201	C19	05.11.2017	BDS-3M-CAST	BDS-3M-CAST
beidou3m2	MEO-2	43002	2017-069B	C202	C20	05.11.2017	BDS-3M-CAST	BDS-3M-CAST
beidou3m3	MEO-3	43208	2018-018B	C206	C21	12.02.2018	BDS-3M-CAST	BDS-3M-CAST
beidou3m4	MEO-4	43207	2018-018A	C205	C22	12.02.2018	BDS-3M-CAST	BDS-3M-CAST
beidou3m5	MEO-5	43581	2018-062A	C209	C23	29.07.2018	BDS-3M-CAST	BDS-3M-CAST
beidou3m6	MEO-6	43582	2018-062B	C210	C24	29.07.2018	BDS-3M-CAST	BDS-3M-CAST
beidou3m11	MEO-11	43603	2018-067B	C212	C25	24.08.2018	BDS-3M-SECM-A	BDS-3M-SECM-A
beidou3m12	MEO-12	43602	2018-067A	C211	C26	24.08.2018	BDS-3M-SECM-A	BDS-3M-SECM-A
beidou3m7	MEO-7	43107	2018-003A	C203	C27	11.01.2018	BDS-3M-SECM-A	BDS-3M-SECM-A
beidou3m8	MEO-8	43108	2018-003B	C204	C28	11.01.2018	BDS-3M-SECM-A	BDS-3M-SECM-A
beidou3m9	MEO-9	43245	2018-029A	C207	C29	29.03.2018	BDS-3M-SECM-A	BDS-3M-SECM-A
beidou3m10	MEO-10	43246	2018-029B	C208	C30	29.03.2018	BDS-3M-SECM-A	BDS-3M-SECM-A
beidou3m13	MEO-13	43622	2018-072A	C213	C32	19.09.2018	BDS-3M-CAST	BDS-3M-CAST SAR-A
beidou3m14	MEO-14	43623	2018-072B	C214	C33	19.09.2018	BDS-3M-CAST	BDS-3M-CAST SAR-A
beidou3m15	MEO-15	43648	2018-078B	C216	C34	15.10.2018	BDS-3M-SECM-A	BDS-3M-SECM-A*
beidou3m16	MEO-16	43647	2018-078A	C215	C35	15.10.2018	BDS-3M-SECM-A	BDS-3M-SECM-A*
beidou3m17	MEO-17	43706	2018-093A	C218	C36	18.11.2018	BDS-3M-CAST	BDS-3M-CAST*
beidou3m18	MEO-18	43707	2018-093B	C219	C37	18.11.2018	BDS-3M-CAST	BDS-3M-CAST*
beidou3m19	MEO-19	44864	2019-090A	C227	C41	16.12.2019	BDS-3M-CAST	BDS-3M-CAST
beidou3m20	MEO-20	44865	2019-090B	C228	C42	16.12.2019	BDS-3M-CAST	BDS-3M-CAST
beidou3m21	MEO-21	44794	2019-078B	C226	C43	23.11.2019	BDS-3M-SECM-B	BDS-3M-SECM-B
beidou3m22	MEO-22	44793	2019-078A	C225	C44	23.11.2019	BDS-3M-SECM-B	BDS-3M-SECM-B
beidou3m23	MEO-23	44543	2019-061B	C223	C45	22.09.2019	BDS-3M-CAST	BDS-3M-CAST SAR-B
beidou3m24	MEO-24	44542	2019-061A	C222	C46	22.09.2019	BDS-3M-CAST	BDS-3M-CAST SAR-B

Number of observations

- ILRS successfully started tracking of BDS-3 in February 2023.
- A relatively stable number of observations per month



SLR validation results

	[mm]	BDS-2I	BDS-2M	BDS-3M-CAST	BDS-3M-CAST SAR-A	BDS-3M-CAST SAR-B	BDS-3M-CAST*	BDS-3M-SECM-A	BDS-3M-SECM-A*	BDS-3M-SECM-B
COD	**MEAN**	56	18	51	11	81	54	-22	-39	-2
ESA		21	-15	46	-30	58	42	-16	-18	-3
WUM		21	11	45	-8	58	34	2	-6	5
COD	**STD**	71	59	**24**	**30**	56	**27**	**24**	**28**	110
ESA		51	**18**	**19**	**29**	82	**27**	**20**	**20**	112
WUM		52	39	**21**	**28**	74	**26**	**26**	**26**	114
COD	**RMS**	90	61	56	32	99	61	33	48	110
ESA		55	**24**	50	42	101	49	**25**	**27**	112
WUM		56	40	49	**29**	94	42	**26**	**27**	114

- The standard deviation (STD) of SLR residuals is largely consistent among the majority of BDS-3M-CAST and BDS-3M-SECM-A satellites, ranging from 19 to 28 mm.