SLR Validation of BeiDou-3 MEO Orbits
Insights from the First Year of Tracking

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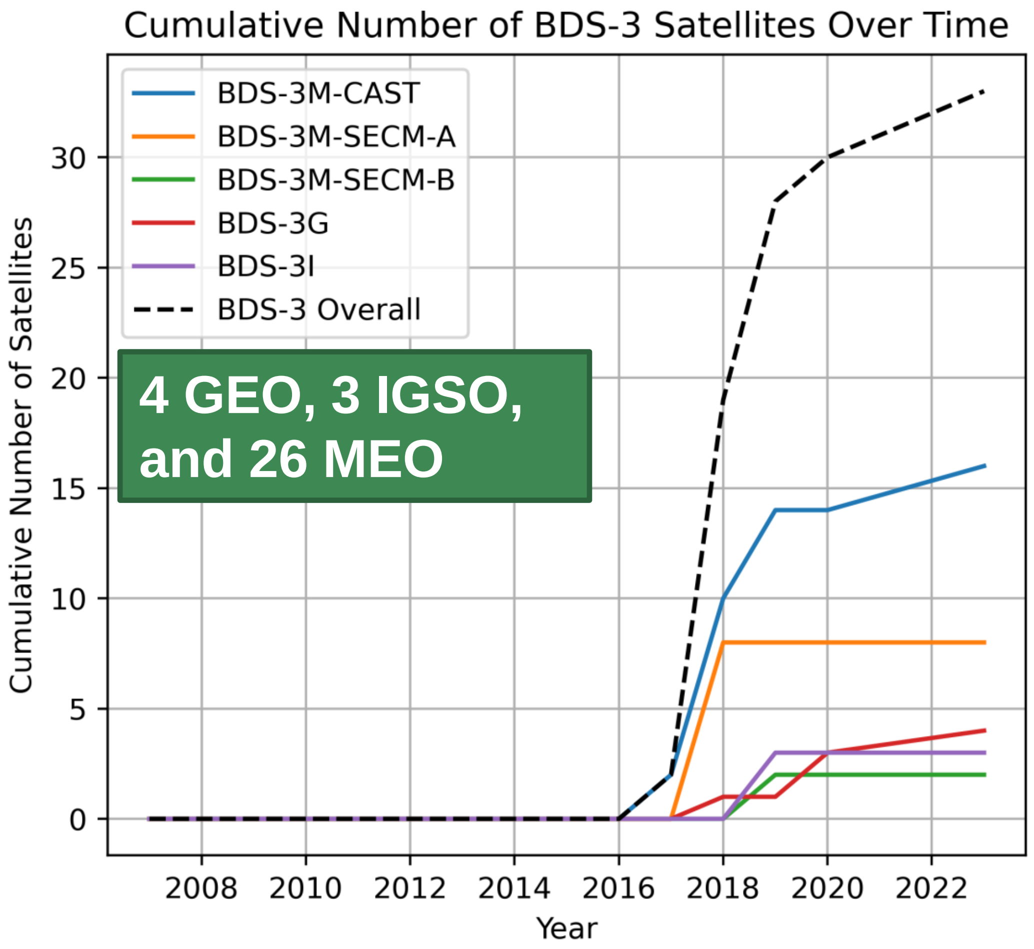
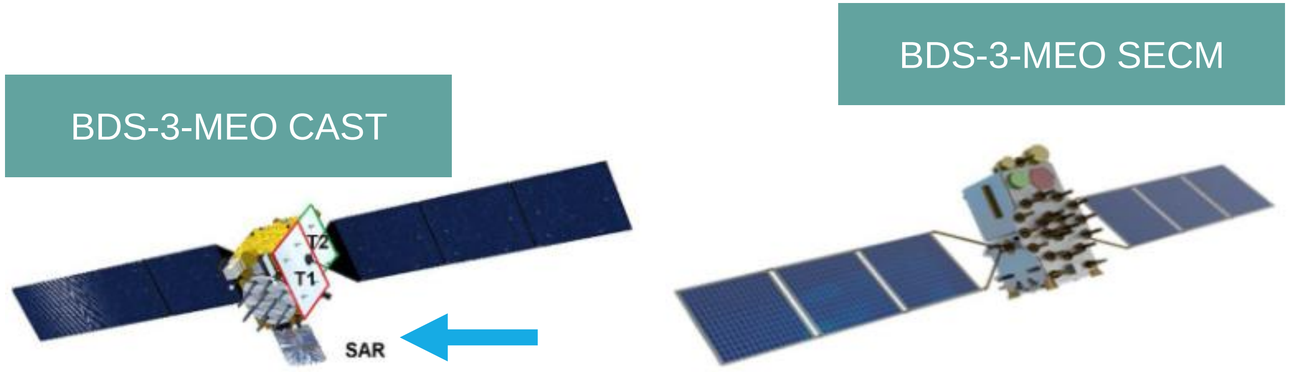
05/09/2024 – ILRS NESC Meeting

BDS-3 Overview





10 satellites manufactured by Shanghai Engineering Center for Microsatellites (SECM) and 16 by China Academy of Space Technology (CAST).

- Within the SECM group of satellites, metadata differentiate between SECM-A and -B satellites, which have different dimensions.
- 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, C45/C46.

- All the BDS-3 satellites are equipped with Laser Retroreflector Array, but till 2023 only 4 were tracked.
- In January 2023, **the International Laser Ranging Service approved tracking 20 additional BDS-3 MEO satellites.**

BDS-3 Tracking - Background

- 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 studies of the individual BDS-3 MEO satellites show that: Orbit modelling is challanging, especially Solar radiation pressure (SRP)

Steigenberger, P. et al. BeiDou Orbits and Clocks (2022) Tour de l'IGS 4th Stop: BDS Constellation Spotlight. 27 September 2022. https://files.igs.org/pub/resource/pubs/workshop/2022/TourdelIGS4_04_Steigenberger.pdf

We may distinguish more groups of satellites than reported in metadata, eg., based on the patterns in the SRP model parameters (eg., Zajdel et al. 2022) or estimated phase center patterns (eg., Huang et al. 2023)

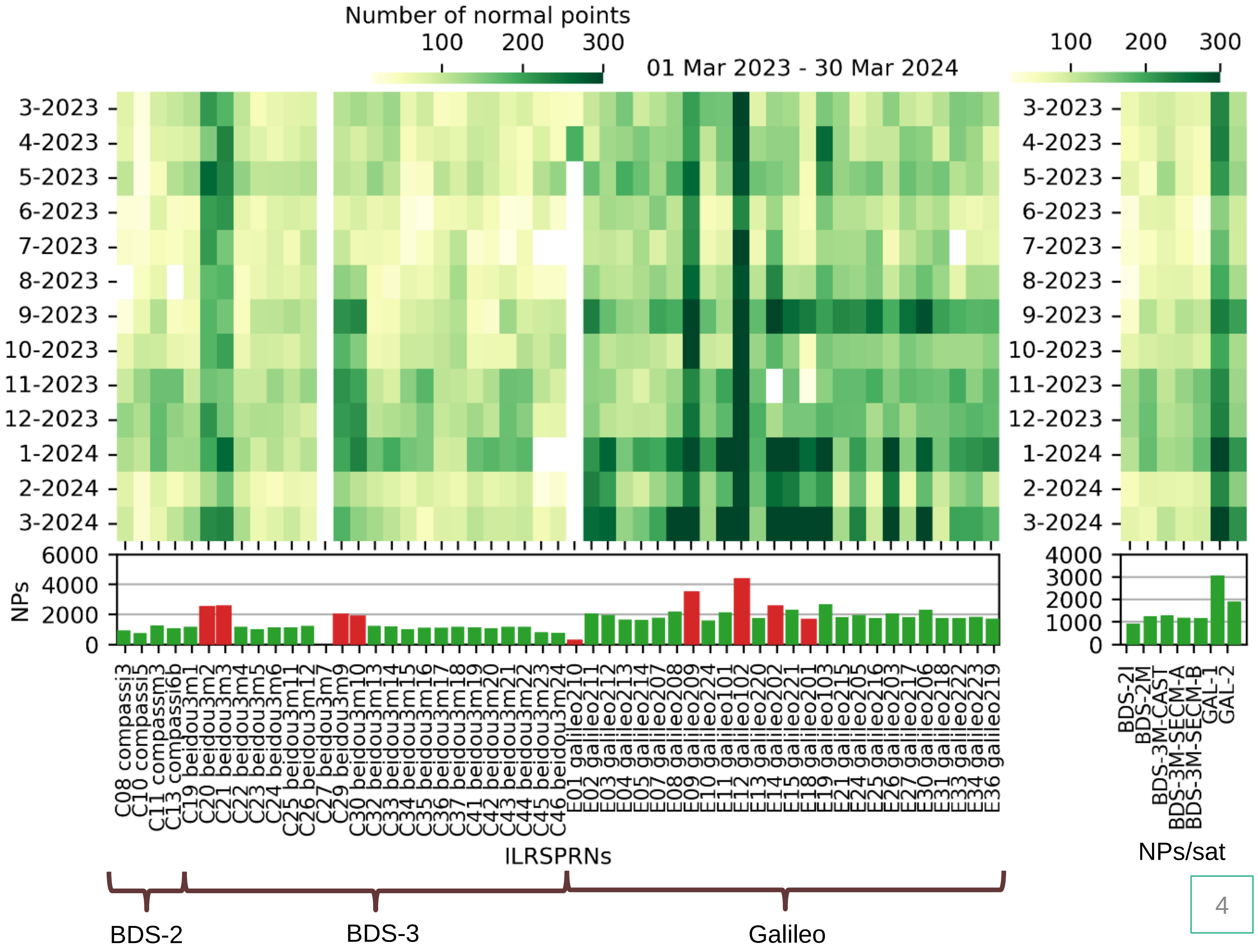
Zajdel, R., Steigenberger, P. & Montenbruck, O. On the potential contribution of BeiDou-3 to the realization of the terrestrial reference frame scale. GPS Solut 26, 109 (2022). https://doi.org/10.1007/s10291-022-01298-0

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*

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

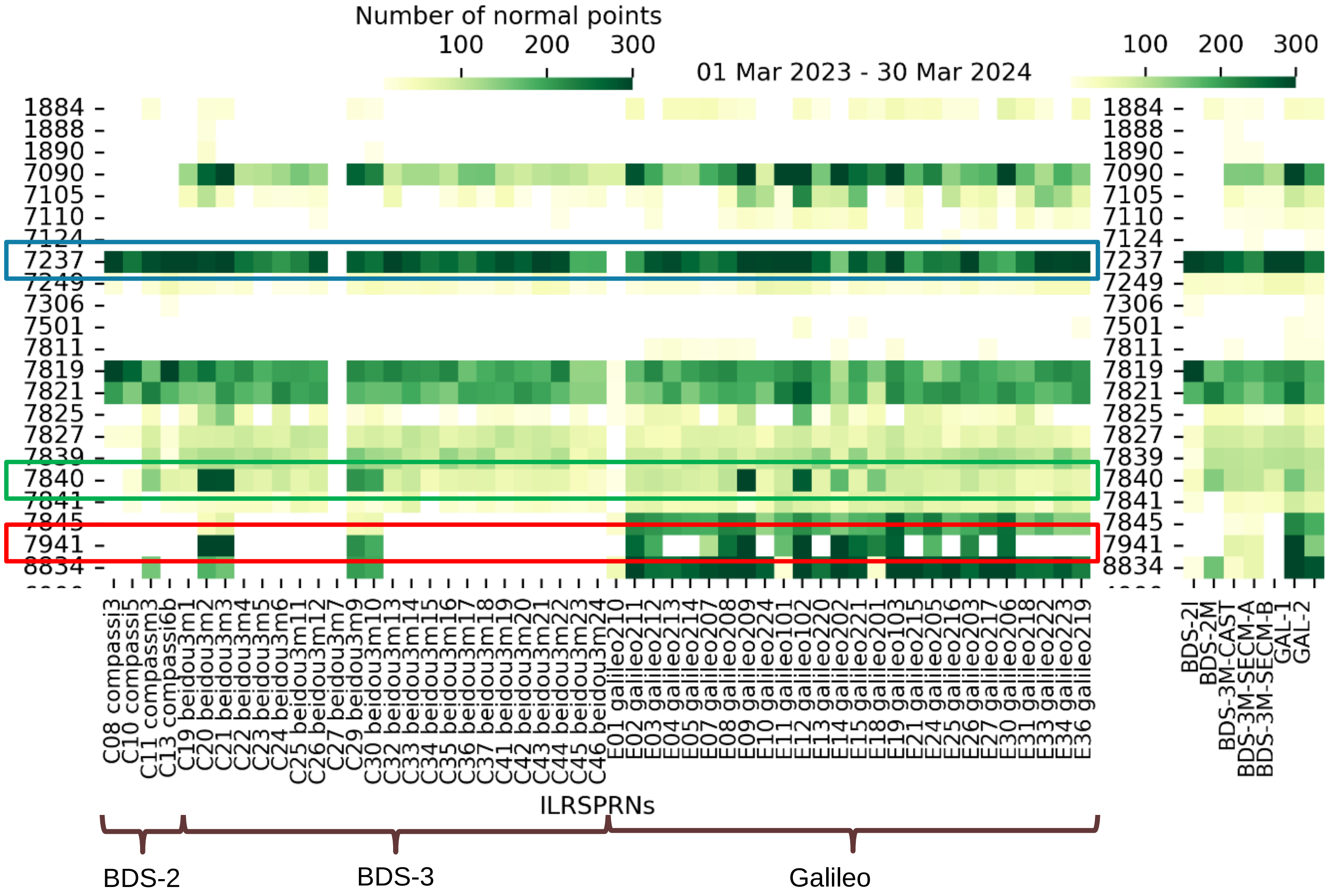
SLR Tracking Performance

- **The priority satellites C20/C21/C29/C30** have **two times more observations** compared to the other BDS.
- **The stations provide almost two times more observations for Galileo** than for the BDS-3 satellites for the non-ILRS priority satellites.
- The increased number of Galileo observations at the beginning of 2024 arises from the ILRS support to Galileo for Science Project (G4S_2.0)

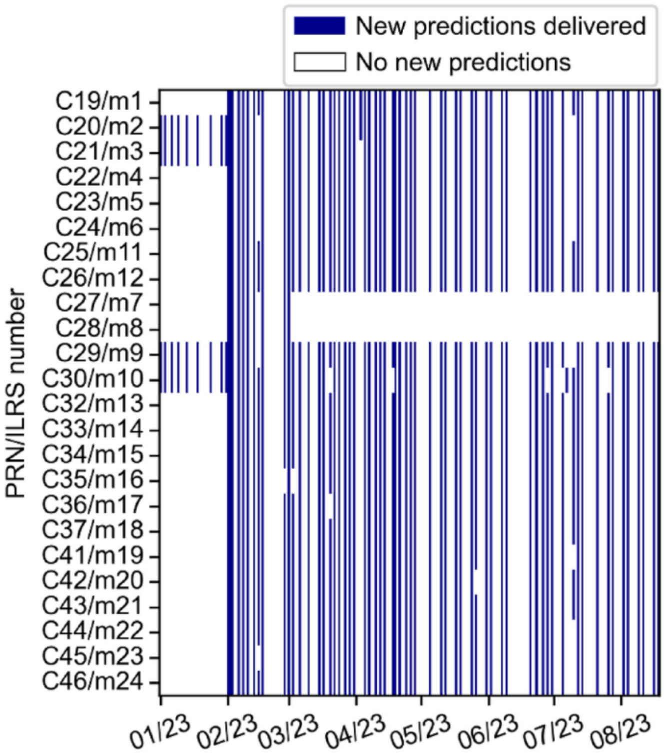


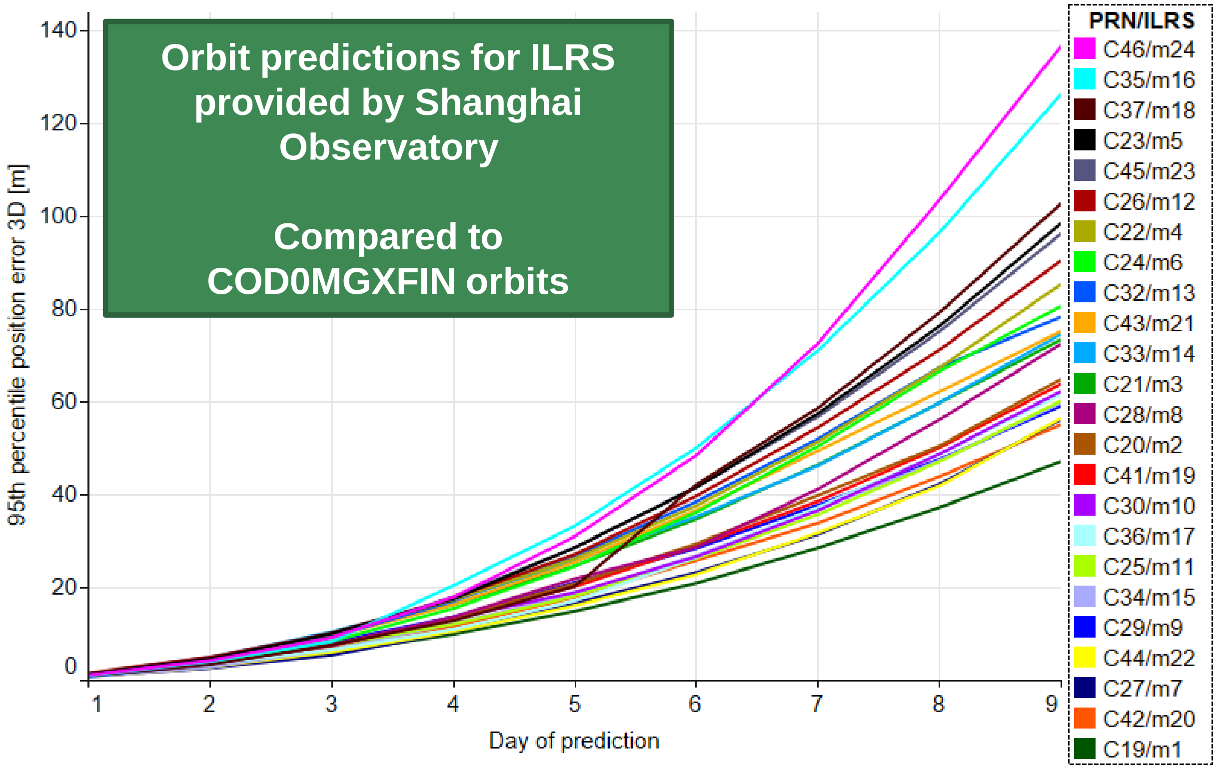
SLR Tracking Performance

- **Over half of the normal points to BDS-3 MEO satellites were collected by 5 out of the 24 active laser stations.**
- **In the ILRS network, we can distinguish different groups of stations:**
  - Stations that track all the targets almost equally.
  - Stations that strictly follow the ILRS priority list.
  - Stations that follow the ILRS priority list but also provide observations to non-priority satellites, albeit with less intensity.



Orbit Predictions

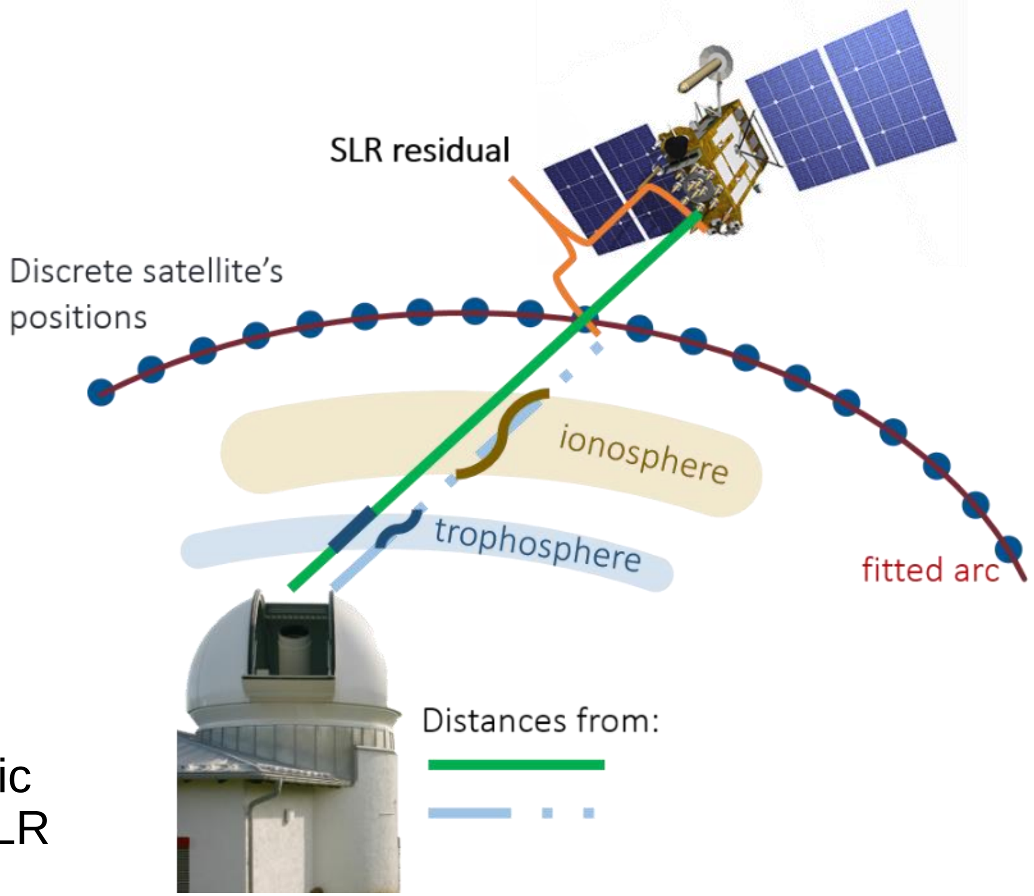




- The average time between successive releases of these new satellite prediction files is approximately 3 days, with occasional intervals of 5 to 10 days.
- No predictions for BeiDou-3M7 (C27) and BeiDou-3M8 (C28) from the beginning of March 2023. Stations failed to get returns from either satellite despite good predictions.
- Prediction quality reaches 10 m and 100 m after 3 and 9 days, respectively. No correlation found between the prediction quality and the number of observations.

SLR Validation

- Precise orbits delivered by:
  Center for Orbit Determination in Europe (COD)
  European Space Agency (ESA)
  GFZ German Research Centre for Geosciences
  Wuhan University (WUM)
  Information and Analysis Center (IAC)
  Shanghai Observatory (SHA)
- Stations: SLRF2020
- Satellites: most of the background models consistent with the validated orbits
  - mm level orbit reconstruction
- Software: Bernese GNSS Software 5.4
- The SLR residuals have been corrected for detector-specific biases aiming to increase the internal consistency of the SLR dataset. Consistently with Zajdel et al. (2023)



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

Selected BDS-3 Orbit Modeling Options

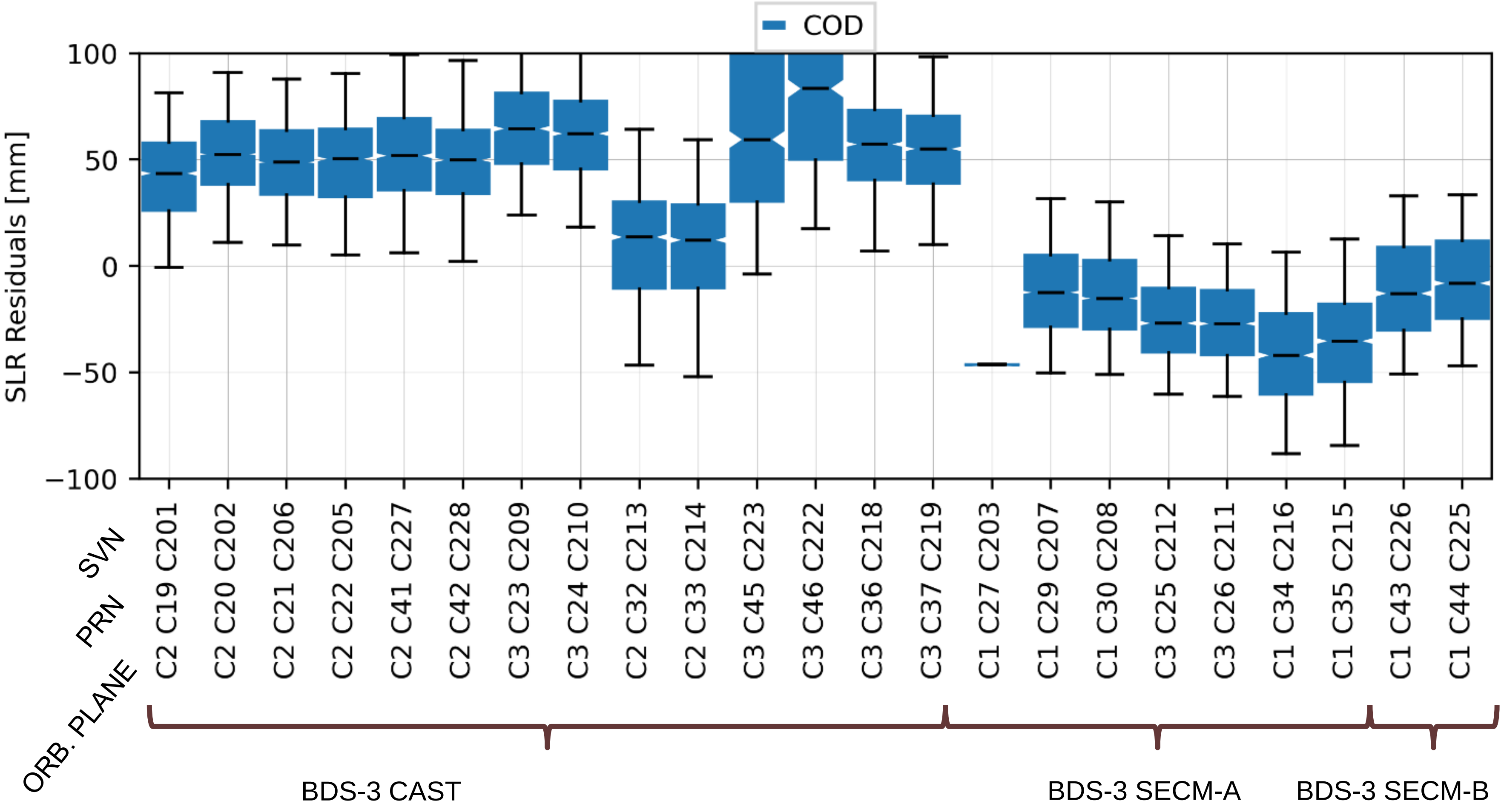
Abb.	Arc length	A priori SRP	SRP parameters	Albedo/IR
COD	72 h	None	ECOM-2 D0,Y0,B0,BC,BS, D2C, D2S	--
ESA	24 h	Box-wing	ECOM D0,Y0,B0,BC,BS; 1/rev in along-track A0, AC, AS	YES
GFZ	24 h	None	ECOM D0,Y0,B0,BC,BS	--
IAC	48 h	Box-wing	ECOM Sc, Y0, BC, BS $\lvert\beta\rvert < 5°$ D0, B0 $\lvert\beta\rvert > 5°$ D1C, D1S	YES
SHA	24 h	Box-wing	ECOM D0,Y0,B0,BC,BS	--
WUM	24 h	Box-wing	ECOM D0,Y0,B0,BC,BS	YES

- **Processing options as used by different ACs differ in terms of the way that they handle SRP:**
  - Different set of empirical parameters
  - Different arc lengths
  - Usage a priori box-wing models; source of coefficients

Steigenberger, P. et al. BeiDou Orbits and Clocks (2022) Tour de l'IGS 4th Stop: BDS Constellation Spotlight. 27 September 2022.
https://files.igs.org/pub/resource/pubs/workshop/2022/TourdelIGS4_04_Steigenberger.pdf

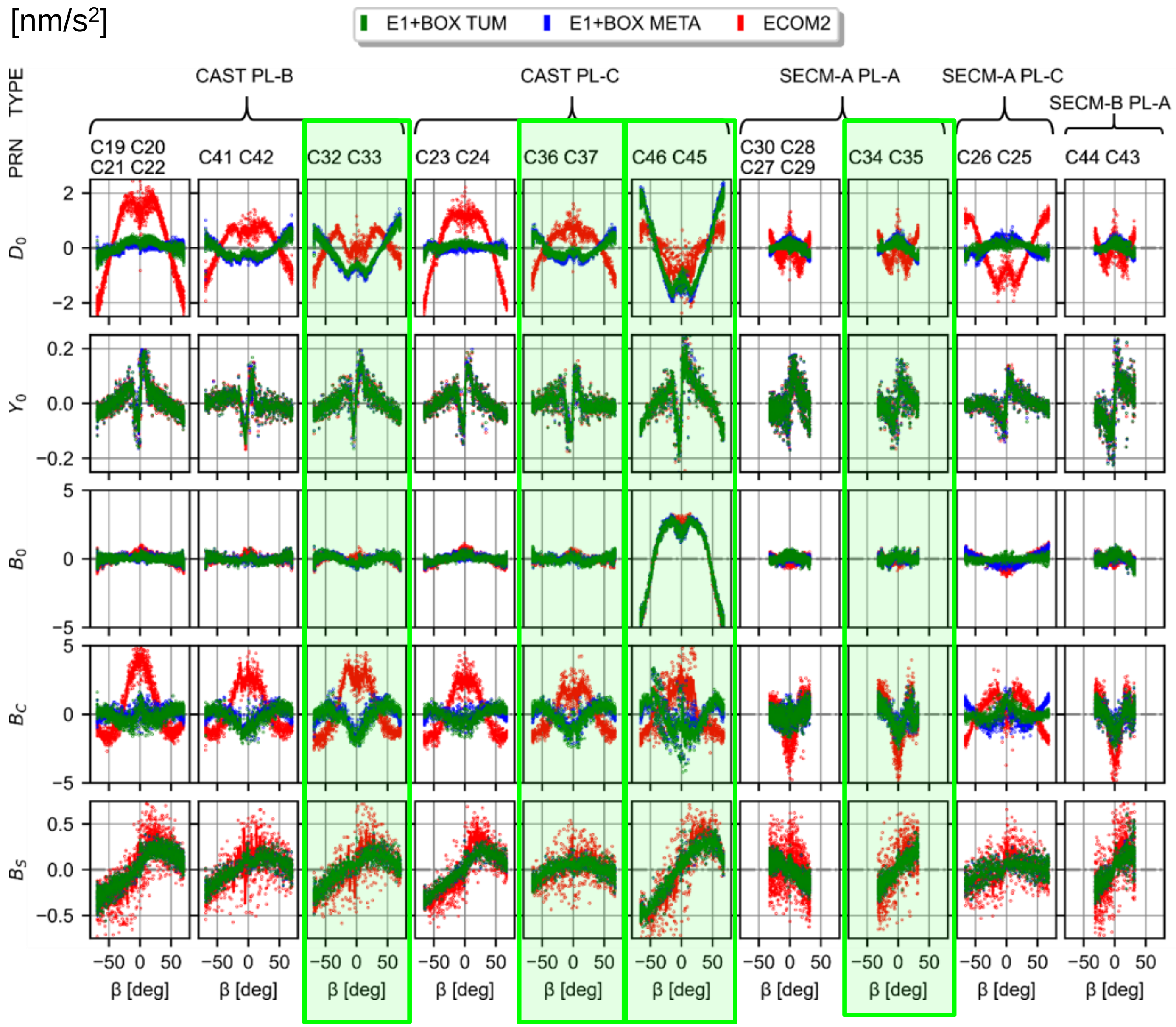
SLR Validation

- Mean SLR residuals at the level of **+50 and -20 mm**, for **CAST and SECM**
- The launch duos have similar residual characteristics, showing that these are the most consistent, especially for SECM, satellites.
- We see more groups than the metadata indicates.



Empirical CODE Orbit Model Parameters

- More different groups of satellites, which are placed on a given orbital plane and are characterized by similar patterns in the estimated ECOM parameters.

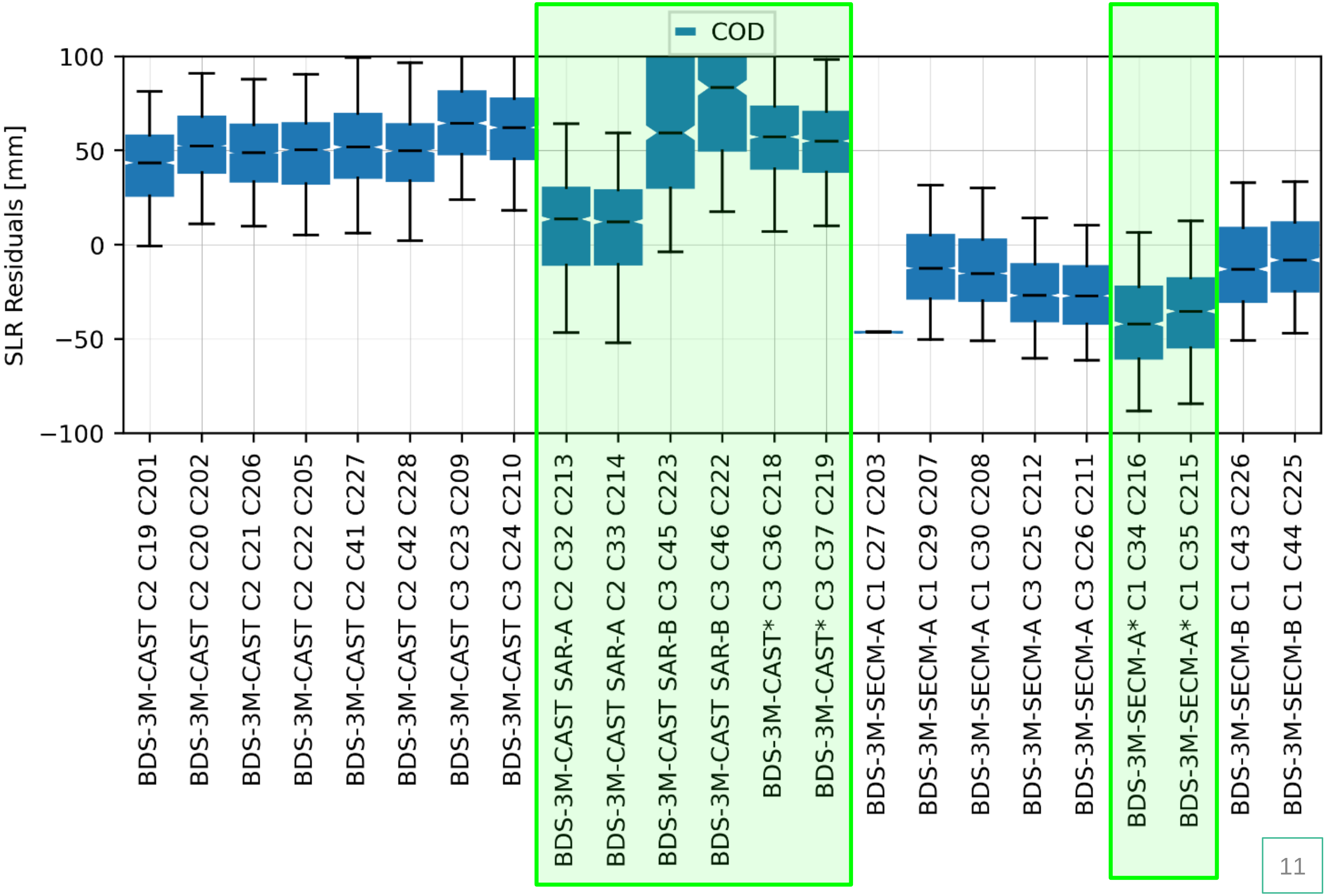


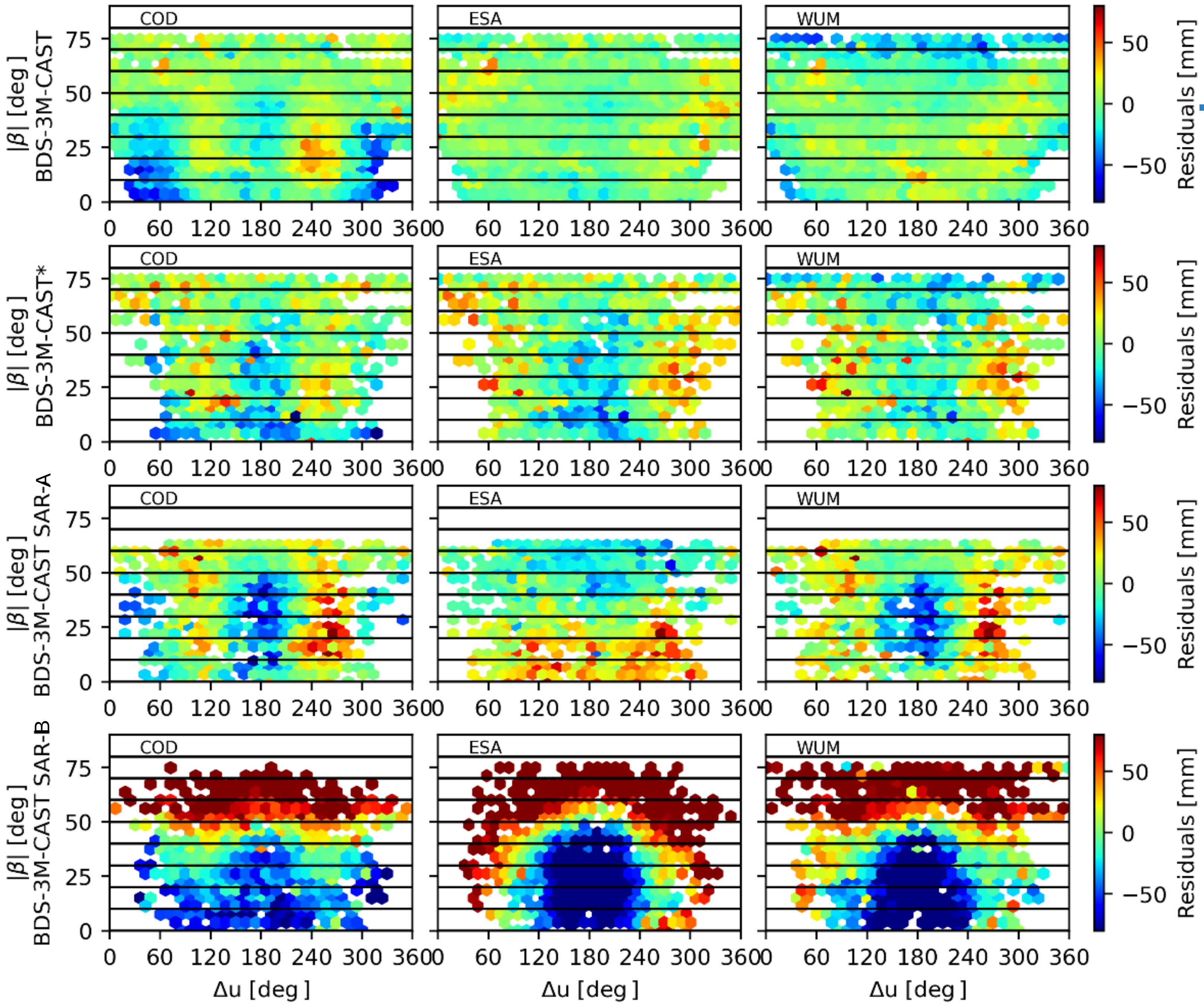
Zajdel, R., Steigenberger, P. & Montenbruck, O. On the potential contribution of BeiDou-3 to the realization of the terrestrial reference frame scale. GPS Solut 26, 109 (2022). https://doi.org/10.1007/s10291-022-01298-0

Duan B, Hugentobler U, Selmke I, Marz S, Killian M, Rott M (2022) BeiDou satellite radiation force models for precise orbit determination and geodetic applications. IEEE Trans Aerosp Electron Syst. https://doi.org/10.1109/TAES.2021.3140018

SLR Validation

- The groups detailed from the analysis of empirical parameter are reflected in a different distribution of SLR residuals.
- four BDS-3 CAST (C32, C33, C45, C46) satellites and two SECM-B satellites (C43, C44), are equipped with additional SAR equipment.



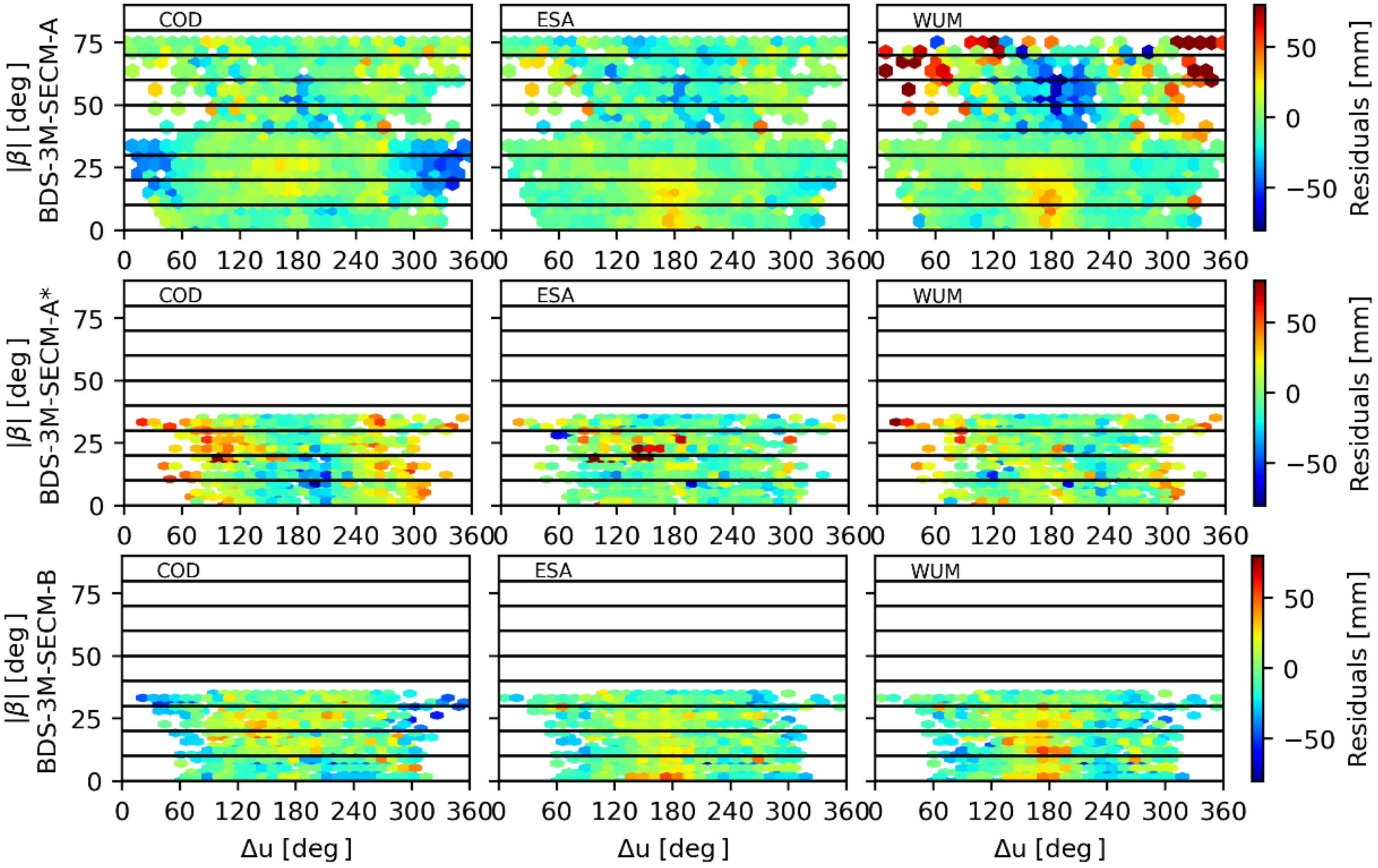


SLR Validation

BDS-3M-CAST

- The 3 ACs with the best results were selected.
- The orbit modeling deficiencies are visible for most ACs and subgroups of satellites.
- **ESA orbit modelling works great with BDS-3 CAST** satellites (comparable to their Galileo FOC results)
- The SLR residual analysis confirms the validity of grouping satellites, revealing differences in orbit quality and systematic errors.

SLR Validation



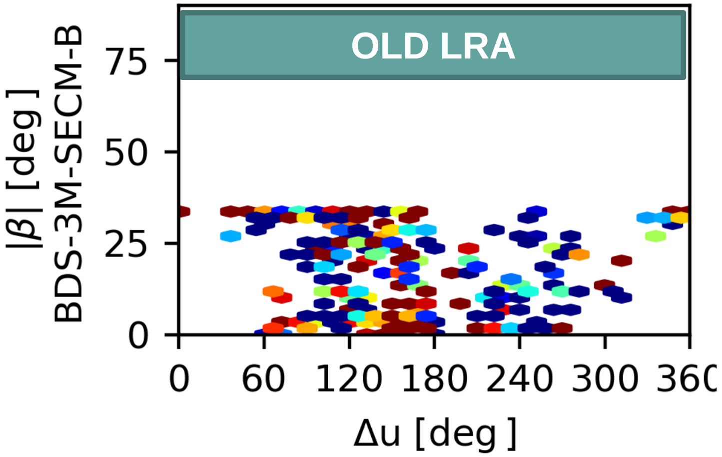
BDS-3M-SECM

- The 3 ACs with the best results were selected.
- The orbit modeling deficiencies are visible for most ACs and subgroups of satellites.
- **ESA orbit modelling works great with BDS-3 SECM-A.** The larger scatter of residuals applies only to high beta angles, i.e. satellites on plane C (C25/26).
- The SLR residual analysis confirms the validity of grouping satellites, revealing differences in orbit quality and systematic errors.

Improvement of Metadata – C43/C44

- The official LRA X- and Y-offset (m) from the BeiDou metadata:
  - SVN225/C44 0.6339 0.4250
  - SVN226/C43 0.6347 0.4248

Zajdel, R., Nowak, A. & Sośnica, K. Satellite laser ranging to BeiDou-3 satellites: initial performance and contribution to orbit model improvement. *GPS Solut* **28**, 100 (2024). https://doi.org/10.1007/s10291-024-01638-2



- The updated values by CSNO:
  - SVN225/C44 -1.062 -0.287
  - SVN226/C43 -1.061 -0.287

The RMS of SLR residuals has been reduced from 150 to 20 mm!

- The estimated values by ESA and DLR:
  - SVN225/C44 -1.085 -0.315 | -1.048 -0.264
  - SVN226/C43 -1.068 -0.332 | -1.060 -0.300

Conclusions

- **The ILRS network successfully tracks almost entire BDS-3 constellation**.
  - As of March 2023, the ILRS network observes 22 BDS-3 satellites instead of the full 24 due to the suspension of orbit prediction provision for C27 and C28 satellites.
- SLR validation revealed more satellite groups in the BDS-3 MEO constellation than documented in official metadata.
- Current **orbit modeling works well for 16 out of 22 BDS-3 MEO** satellites (CAST, SECM-A, SECM-B); improving modeling for the remaining satellites is **a challenge to be faced**.

Problematic satellites: C32/C33 (BDS-3M-CAST SAR-A), C45/C45 (BDS-3M-CAST SAR-B), C34/C35 (BDS-3M-SECM-A*)

- Continued ILRS network support and increased observations for specific satellites that would be helpful to improve orbit modeling.
- Current ILRS recommendation: C20/C21 (CAST), C29/C30 (SECM-A)
  → C20 (CAST) C29 (SECM-A) C32 (CAST SAR-A) C34 (CAST*) C45 (CAST SAR-B) C36 (CAST*) C43 (SECM-B)

Geodetic observatory Pecný

WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

International Association of Geodesy

IGS INTERNATIONAL GNSS SERVICE

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Central Bohemia Region

MERIT ...brains in motion

Thank you

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Zajdel, R., Nowak, A. & Sośnica, K. Satellite laser ranging to BeiDou-3 satellites: initial performance and contribution to orbit model improvement. *GPS Solut* **28**, 100 (2024). https://doi.org/10.1007/s10291-024-01638-2

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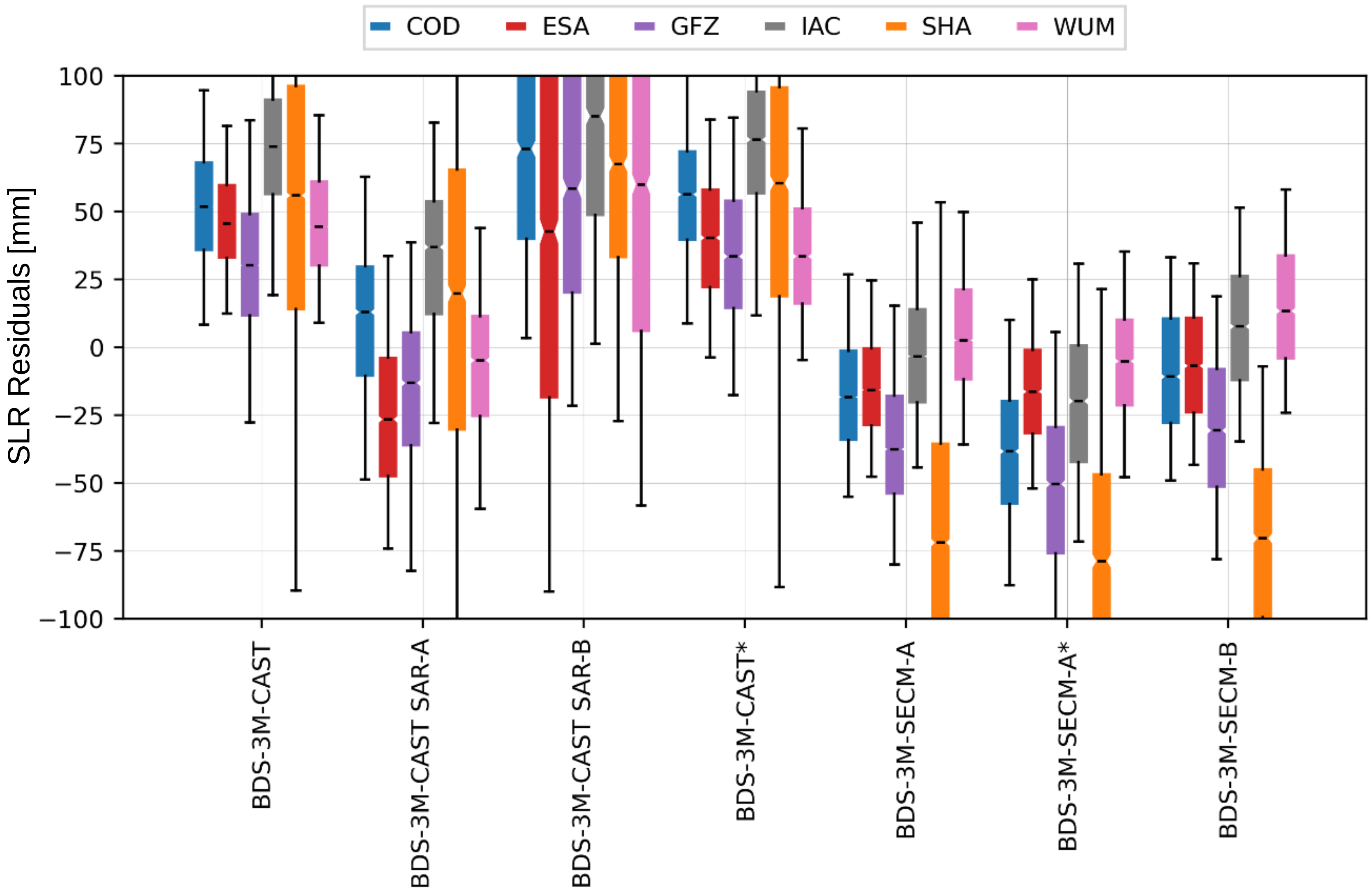
SLR Validation

STANDARD DEVIATION OF SLR RESIDUALS [mm]	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	GAL-2
COD	26.4	32.9	56.3	27.6	25.4	30.9	25.9	21.5
ESA	21.7	32.4	84.6	26.9	22.2	35.1	23.6	20.2
GFZ	34.9	37.4	65.9	31.9	29.4	37.7	29.8	26.4
IAC	29.8	33.6	58.0	33.0	27.5	34.2	27.1	23.7
SHA	71.3	80.1	60.0	69.9	64.1	62.6	40.6	26.9
WUM	23.5	31.2	75.2	26.3	27.2	25.2	26.0	22.1

- The different modelling of the BDS-3 orbits implemented by the different ACs results in **large differences** in the outcome of SLR validation.



SLR Validation Details

SATELLITE ID			SLR RESIDUALS [mm]					
SAT TYPE	PLANE	SVN	MEDIAN	MEAN	STD	IQR	RMS	OBS.
BDS-3M-CAST	C2	601	43.5	42.0	25.9	32.1	49.3	1249
		602	52.5	52.6	24.8	29.9	58.2	2934
		605	50.3	49.3	26.6	32.1	56.0	1230
		606	48.7	48.6	24.3	30.3	54.4	3088
		627	51.8	51.9	28.2	34.0	59.1	1222
		628	49.8	49.0	28.0	30.1	56.4	1143
	C3	609	64.5	64.3	25.6	33.4	69.2	1068
		610	62.2	61.3	26.0	32.1	66.6	1207
BDS-3M-CAST SAR-A	C2	613	13.6	10.8	32.7	41.0	34.4	1281
		614	12.2	9.3	33.1	39.4	34.3	1282
BDS-3M-CAST SAR-B	C3	622	83.4	92.9	53.5	88.3	107.2	1006
		623	59.4	74.2	57.5	85.6	93.9	1019
BDS-3M-CAST*	C3	618	57.2	57.1	28.3	33.1	63.7	1143
		619	55.1	54.6	26.9	32.0	60.8	1216
BDS-3M-SECM-A	C1	603	-46.4	-46.4	0.4	0.3	46.4	2
		607	-12.4	-11.0	24.9	33.8	27.3	2221
		608	-15.2	-12.9	25.2	32.7	28.3	2127
	C3	611	-27.1	-26.2	22.4	30.7	34.4	1277
		612	-26.9	-25.5	24.6	30.4	35.4	1176
BDS-3M-SECM-A*	C1	615	-35.3	-34.7	33.2	36.9	48.0	1202
		616	-42.0	-41.4	27.9	38.2	49.9	1127
BDS-3M-SECM-B	C1	625	-8.1	-7.1	25.4	36.8	26.4	1251
		626	-12.9	-10.6	26.3	39.3	28.3	1234

Galileo for Science (G4S) Tracking Campaign

4-Sep-2024

G4S Campaign Summary NP Totals (current week and aggregate)

Galileo for Science Campaign Normal Point Totals (Current Week)																
Pad	Location	101	102	103	201	202	203	205	206	208	209	210	211	212	221	**Total**
1873	Simeiz	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
1884	Riga	0	0	0	0	0	0	4	8	2	0	7	9	0	0	**30**
7090	Yarragadee	10	21	31	13	14	11	0	0	4	11	2	1	11	7	**136**
7105	Greenbelt	0	4	0	0	0	0	0	0	0	0	0	0	0	0	**4**
7110	Monument Peak	0	0	0	0	2	0	17	0	0	0	13	0	0	0	**32**
7124	Tahiti	0	0	0	0	0	0	0	0	0	0	0	0	4	0	**4**
7237	Changchun	1	1	4	12	16	7	10	8	4	4	10	3	5	7	**92**
7249	Beijing	0	0	2	2	3	1	0	2	2	0	2	5	4	0	**23**
7306	Tsukuba	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
7396	Wuhan	6	0	0	6	5	2	4	3	0	0	0	11	0	6	**43**
7501	Hartebeesthoek	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
7701	Izana	3	0	7	1	0	0	10	8	7	5	7	9	7	4	**68**
7811	Borowiec	0	0	0	2	0	0	0	0	0	0	0	0	0	0	**2**
7819	Kunming	2	2	2	0	2	2	2	0	0	2	1	0	0	0	**15**
7821	Shanghai	0	4	5	6	0	0	3	3	3	0	0	4	2	0	**30**
7825	Mt Stromlo	0	36	0	39	36	16	33	22	11	31	20	18	0	3	**265**
7827	Wettzell	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
7839	Graz	0	0	0	0	0	0	2	2	0	0	0	1	0	2	**7**
7840	Herstmonceux	4	8	0	6	10	4	4	0	3	6	2	4	2	0	**53**
7841	Potsdam	5	9	0	3	8	7	5	3	1	0	11	2	2	7	**63**
7845	Grasse	3	8	4	12	5	4	11	0	0	3	4	3	0	0	**57**
7941	Matera	0	18	0	110	100	0	0	0	0	30	22	21	0	0	**301**
8834	Wettzell	3	17	7	5	9	5	11	7	6	3	9	15	2	2	**101**
	Totals	37	128	62	217	210	59	116	66	43	95	110	106	39	38	**1326**

Galileo for Science Campaign Normal Point Totals (Aggregate)																
Pad	Location	101	102	103	201	202	203	205	206	208	209	210	211	212	221	**Total**
1873	Simeiz	0	0	0	0	0	0	3	0	0	0	5	0	0	0	**8**
1884	Riga	0	24	70	26	0	0	54	52	31	49	55	56	39	21	**477**
7090	Yarragadee	487	512	500	457	457	116	189	295	153	187	251	304	145	260	**4313**
7105	Greenbelt	30	129	55	52	44	60	63	47	87	134	113	78	77	62	**1031**
7110	Monument Peak	46	84	51	0	41	81	74	51	86	71	62	39	102	37	**825**
7124	Tahiti	0	28	0	9	0	0	0	0	4	0	3	0	5	0	**49**
7237	Changchun	117	106	140	59	66	97	79	64	150	157	61	62	168	97	**1423**
7249	Beijing	27	28	20	19	13	19	9	9	19	23	8	9	27	17	**247**
7306	Tsukuba	57	61	75	44	66	67	33	38	75	77	31	42	57	56	**779**
7396	Wuhan	37	44	71	37	41	51	94	76	73	36	57	57	85	52	**811**
7501	Hartebeesthoek	0	5	0	0	0	0	0	0	0	0	0	0	0	0	**5**
7701	Izana	64	47	55	53	39	38	49	53	70	55	51	42	69	50	**735**
7811	Borowiec	6	0	14	10	8	5	0	3	15	6	4	0	0	0	**71**
7819	Kunming	85	90	129	67	75	98	52	75	125	104	72	67	121	114	**1274**
7821	Shanghai	85	95	111	53	43	63	66	84	98	81	51	91	89	64	**1074**
7825	Mt Stromlo	0	177	0	147	173	60	92	84	26	166	59	122	20	18	**1144**
7827	Wettzell	9	9	2	8	9	6	4	4	4	3	3	4	6	6	**77**
7839	Graz	72	88	92	81	44	68	77	94	116	90	79	91	100	101	**1193**
7840	Herstmonceux	108	133	138	106	178	99	90	97	119	210	86	90	132	85	**1671**
7841	Potsdam	69	65	71	58	63	30	65	72	51	44	48	43	68	78	**825**
7845	Grasse	141	149	197	242	218	121	169	202	139	165	217	155	121	123	**2359**
7941	Matera	298	630	485	1011	905	323	248	328	404	737	575	511	302	361	**7118**
8834	Wettzell	18	353	125	119	211	143	129	142	117	209	193	185	96	126	**2166**
	Totals	1756	2857	2401	2658	2694	1545	1639	1870	1962	2604	2084	2048	1829	1728	**29675**

Legend
Elliptical Orbit

G4S Campaign Summary Pass Totals (current week and aggregate)

Galileo for Science Campaign Pass Totals (Current Week)															
Pad	Location	101	102	103	201	202	203	205	206	208	209	210	211	212	221	**Total**
1873	Simeiz															
1884	Riga							1	2	1		2	2			**8**
7090	Yarragadee	3	3	4	3	4	2			2	4	1	1	4	4	**35**
7105	Greenbelt		1													**1**
7110	Monument Peak					1		1				1				**3**
7124	Tahiti													1		**1**
7237	Changchun	1	1	2	3	3	2	2	3	2	1	2	2	2	2	**28**
7249	Beijing			1	1	2	1		1	1		1	2	2		**12**
7306	Tsukuba															
7396	Wuhan	1			1	2	1	1	2				1		1	**10**
7501	Hartebeesthoek															
7701	Izana	1		2	1			3	2	2	2	2	2	2	1	**20**
7811	Borowiec				1											**1**
7819	Kunming	1	1	1		1	1	1			1	1				**8**
7821	Shanghai		1	1	1			1	1	1			1	1		**8**
7825	Mt Stromlo		4		4	5	3	5	3	3	6	4	3		1	**41**
7827	Wettzell															
7839	Graz							1	1				1		1	**4**
7840	Herstmonceux	2	3		1	3	2	1		1	2	1	1	1		**18**
7841	Potsdam	1	2		1	1	2	1	1	1		3	1	1	1	**16**
7845	Grasse	1	1	1	2	1	1	2			1	1	1			**12**
7941	Matera		2		6	6					2	2	2			**20**
8834	Wettzell	2	3	3	2	3	2	3	1	1	2	3	2	1	1	**29**
	Totals	13	22	15	27	32	17	23	17	15	21	24	22	15	12	**275**

Galileo for Science Campaign Pass Totals (Aggregate)															
Pad	Location	101	102	103	201	202	203	205	206	208	209	210	211	212	221	**Total**
1873	Simeiz							1				1				**2**
1884	Riga		4	11	6			11	10	7	9	12	12	9	3	**94**
7090	Yarragadee	99	102	86	104	98	38	60	67	49	54	67	77	47	76	**1024**
7105	Greenbelt	11	23	14	16	11	12	15	12	22	33	23	18	21	18	**249**
7110	Monument Peak	10	15	13		10	12	8	8	13	10	6	5	13	8	**131**
7124	Tahiti		2		3					1		1		2		**9**
7237	Changchun	32	29	38	16	20	28	24	23	43	48	18	23	47	29	**418**
7249	Beijing	10	12	8	8	6	10	5	5	9	10	4	5	14	8	**114**
7306	Tsukuba	21	22	25	18	20	21	14	16	23	30	11	17	24	19	**281**
7396	Wuhan	8	6	15	7	12	11	14	17	17	9	15	14	18	12	**175**
7501	Hartebeesthoek		1													**1**
7701	Izana	16	13	14	15	10	9	13	14	20	15	13	10	18	10	**190**
7811	Borowiec	1		3	3	1	1		1	4	2	1				**17**
7819	Kunming	36	39	54	29	32	40	22	32	52	43	30	27	48	46	**530**
7821	Shanghai	19	23	25	13	10	15	15	18	20	18	12	21	22	14	**245**
7825	Mt Stromlo		20		23	25	12	17	13	8	25	11	18	5	3	**180**
7827	Wettzell	5	6	2	7	6	5	4	4	3	3	3	4	4	6	**62**
7839	Graz	29	28	28	31	24	29	23	30	36	32	27	28	27	31	**403**
7840	Herstmonceux	35	39	34	35	52	26	28	34	36	60	27	29	40	29	**504**
7841	Potsdam	17	12	20	13	15	8	16	21	13	11	15	13	18	18	**210**
7845	Grasse	36	37	44	52	43	26	38	42	36	40	46	34	30	32	**536**
7941	Matera	37	73	39	101	85	33	31	37	40	64	73	60	34	43	**750**
8834	Wettzell	11	71	45	33	50	48	38	42	28	50	46	40	32	43	**577**
	Totals	433	577	518	533	530	384	397	446	480	566	462	455	473	448	**6702**

Legend
Elliptical Orbit

Lessons Learned: 1mm Accurate Local Ties McDonald Geodetic Observatory

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Efforts funded by

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- NASA Research Announcement (NRA) NNH16ZDA001N, Research Opportunities in Space and Earth Science (ROSES-2016), Program Element A.48: Space Geodesy Research (Proposal Number: 16-SGR16-0005) 2017-2019

Publication

- Journal of Geodesy, May 2024
  - Rivera, J., Bettadpur, S., Griffin, J. *et al.* Measuring 1-mm-accurate local survey ties over kilometer baselines at McDonald Geodetic Observatory. *J Geod* **98**, 46 (2024). https://doi.org/10.1007/s00190-024-01853-2

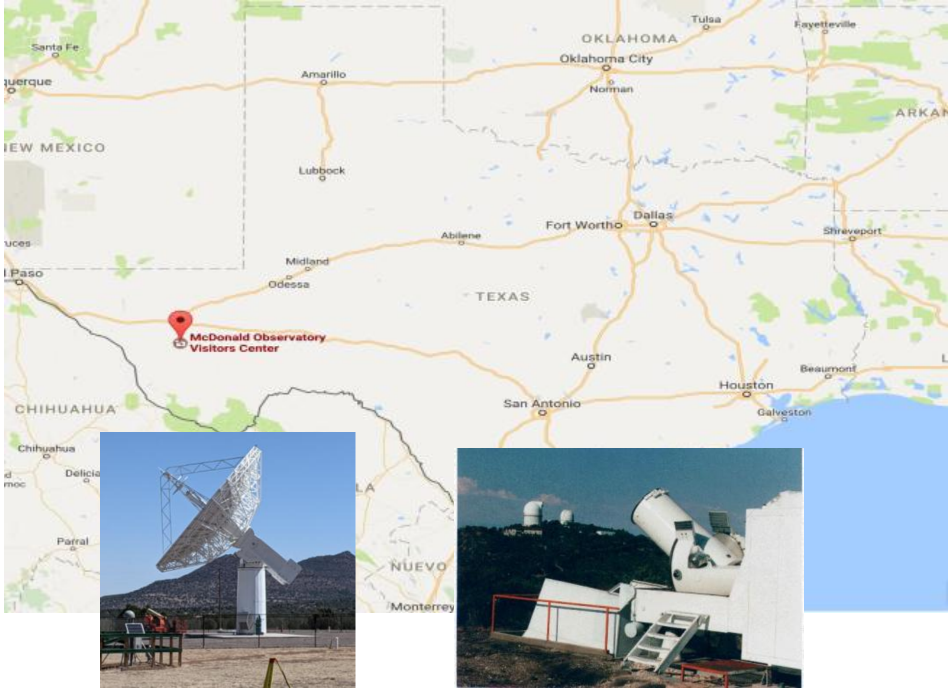
Local Ties at McDonald Observatory

Current Status:

- We have a surveying framework that is precise to sub-mm across a kilometer baseline (>120m elevation change)
- We can repeat the local tie measurement of the local GPS network to 1-2mm over a period of several months
- We can validate the relative accuracy of the local ties with GPS-derived ties to 1-2mm and estimate a scale difference between techniques and local ties

McDonald Geodetic Observatory (MGO)

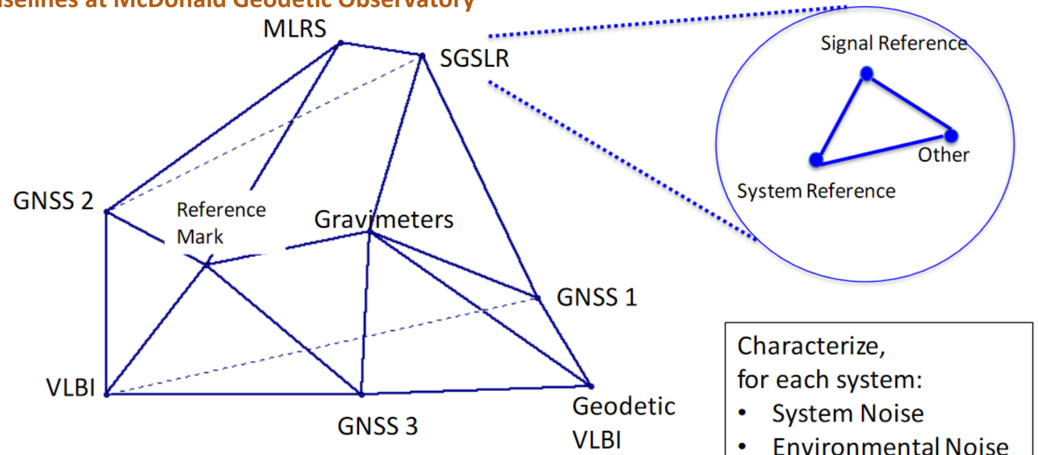
- A joint effort between NASA and the University of Texas at Austin
- The facility includes:
  - 0.8m, 2.1m, 2.7m, and 10m Telescopes
  - Formerly, The McDonald Laser Ranging System (MLRS)
  - Established GNSS station MDO1 and geodetic markers
  - VGOS System
  - GNSS stations MGO2, MGO3, MGO4, MGO5, RTS1
  - Soon: SGSLR System



VGOS VLBI Antenna

McDonald Laser Ranging Station (MLRS)

McDonald Geodetic Observatory (MGO)



Characterize,
for each system:

- System Noise
- Environmental Noise
- Analysis Noise

Time-variable Polygon:

- Measurement
- Characterization
- Application

Define & monitor

- Objective:
  - Accurately measuring and monitoring the local tie polyhedron (3-D relative position vectors) through ground-based precision surveying and metrology procedures
    - Uniquely designed for the McDonald Geodetic Observatory (MGO) core site

Co-location Local Ties

- Accuracy Requirement for next generation tie-vector determination is 1-2 mm (Sarti et al. 2004)
- Average Tie uncertainty in ITRF2020 is >1cm (data from https://itrf.ign.fr/en/local-ties)
  - All ties Down-weighted with minimum uncertainty of 3mm (Altamimi et al, 2011)
  - Ties in disagreement with geodetic techniques down-weighted further
- GGOS recommends core sites to build all instruments within 200m to facilitate local tie accuracy requirements (Pearlman et. al., 2022)

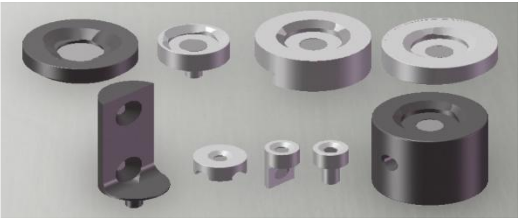
Framework Highlights

- Unique surveying scheme and layout – polyhedral network of local ties with a scale, “braced” reciprocal observations
- Collect raw measurements: no corrections applied in the instrument or in commercial “black box” software
- Manually apply correction models in data processing
- Estimate ties using In-house least squares network solver
- Unique precision and accuracy metrics
- External validation of local tie polyhedron with GPS-derived ties

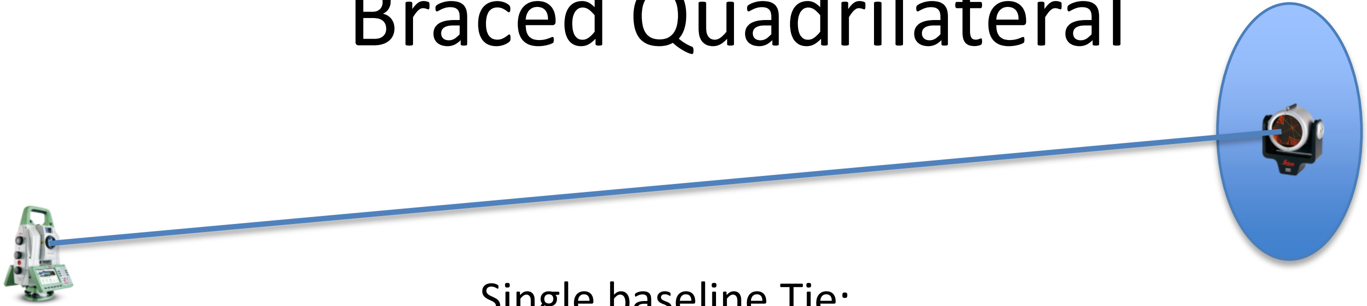
Instrumentation

- Leica TS-30 Total Station
  - ½” Angles, 0.6mm + 1 ppm
  - (Cert: 0.13 mm distance, 0.65” arcsecond, Azimuth, 0.8” Zenith)
- Leica GPH1P Single-Prism Precision Reflectors
- PLX Ball Mounted Hollow Retroreflectors (BMRs)
- MET3 Meteorological Sensor
  - +/- 0.08 hPa accuracy
  - 0.5deg C accuracy
  - 2% Rel. Humidity Accuracy



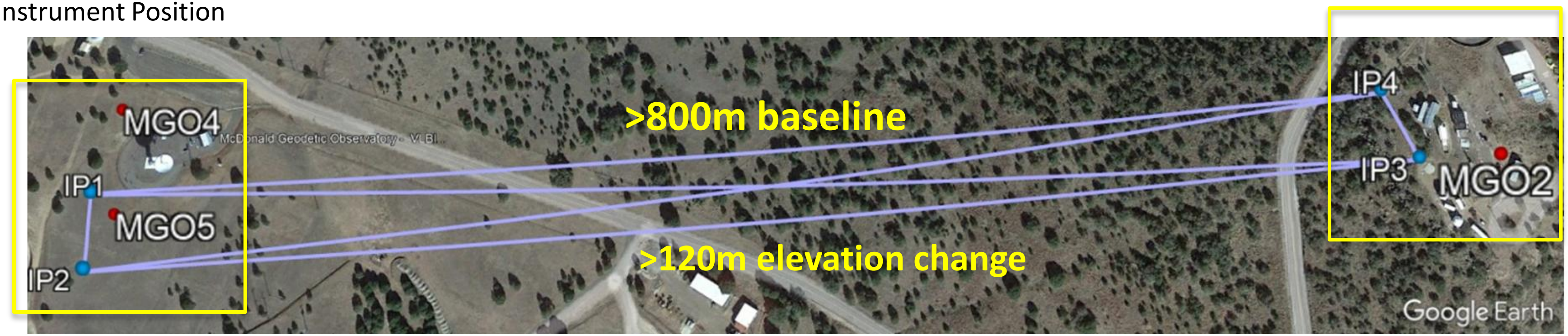



Braced Quadrilateral



Single baseline Tie:
Zenith Bias >> 10cm height error
Azimuth Bias > 1cm horizontal error

IP = Instrument Position

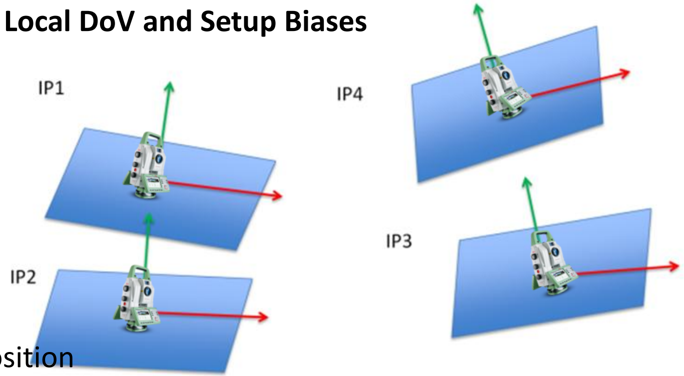


Reciprocal, Cross-braced km-Baseline Observations

Braced Quadrilateral

Instrument Positions (IP) in Local Surveys

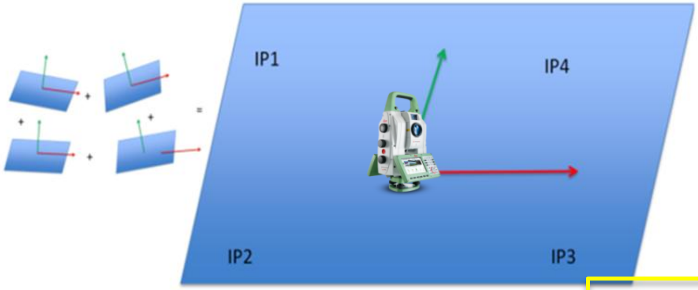
Local DoV and Setup Biases

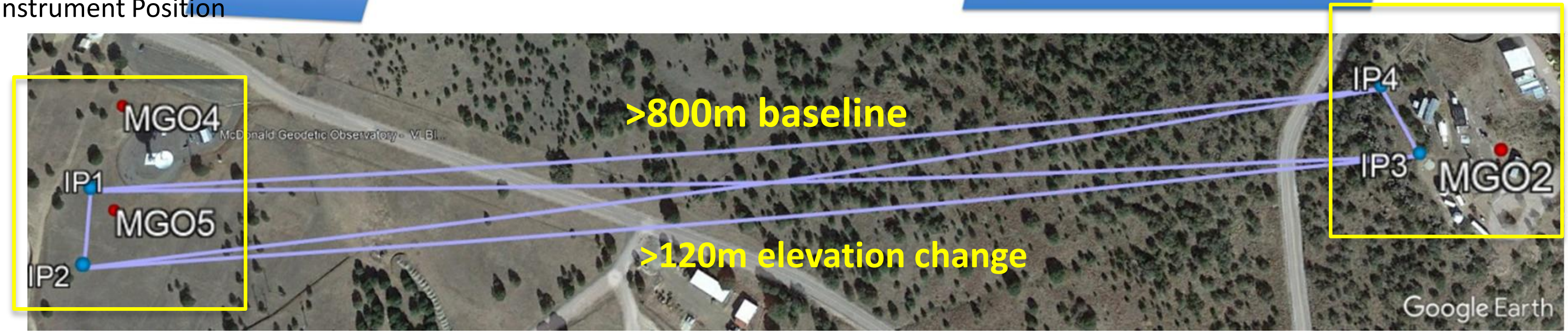


IP = Instrument Position

IP Local Frames Combine to Single Frame Survey

via estimated 3-D rotations per IP local frame





Reciprocal, Cross-braced km-Baseline Observations

Braced Quadrilateral

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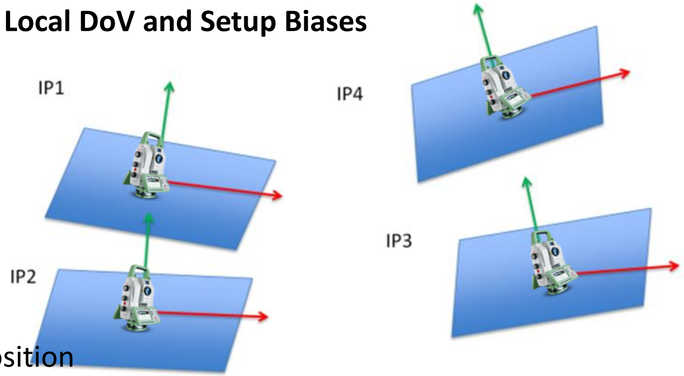

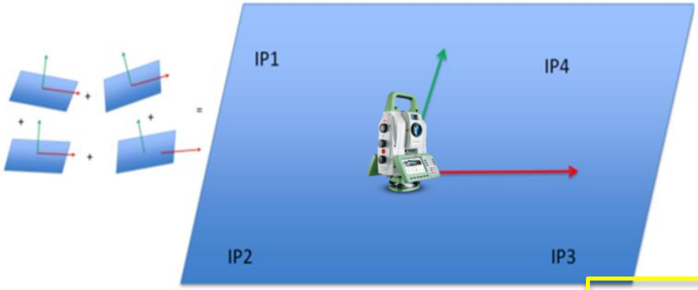

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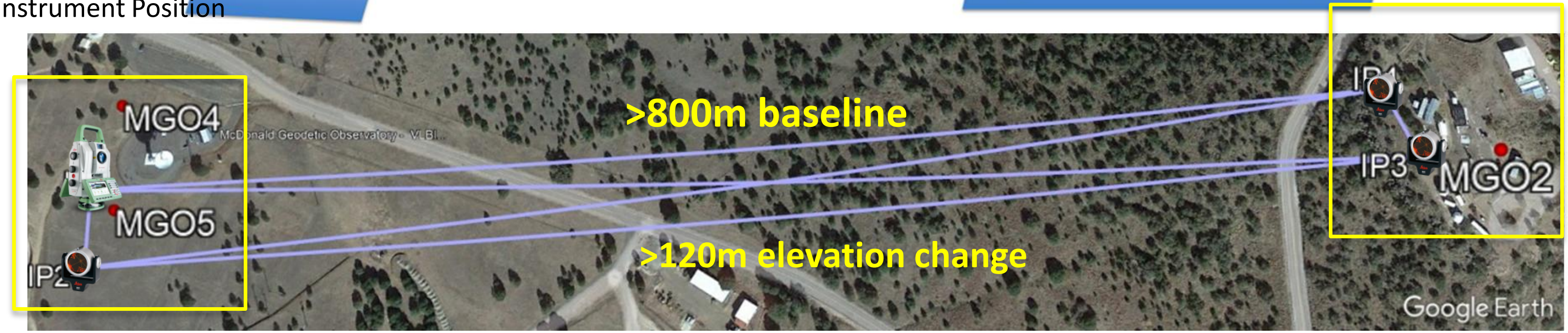

Reciprocal, Cross-braced km-Baseline Observations

Braced Quadrilateral

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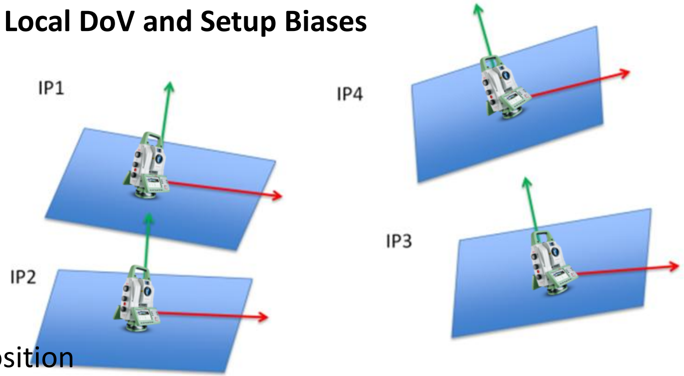

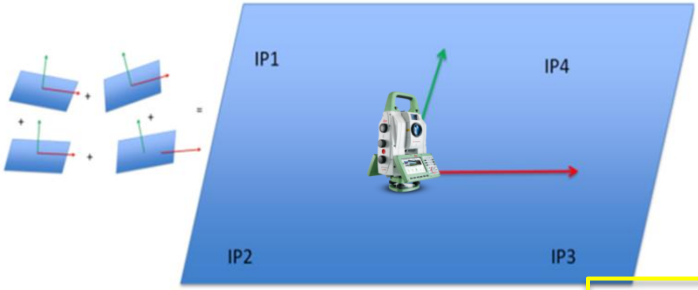

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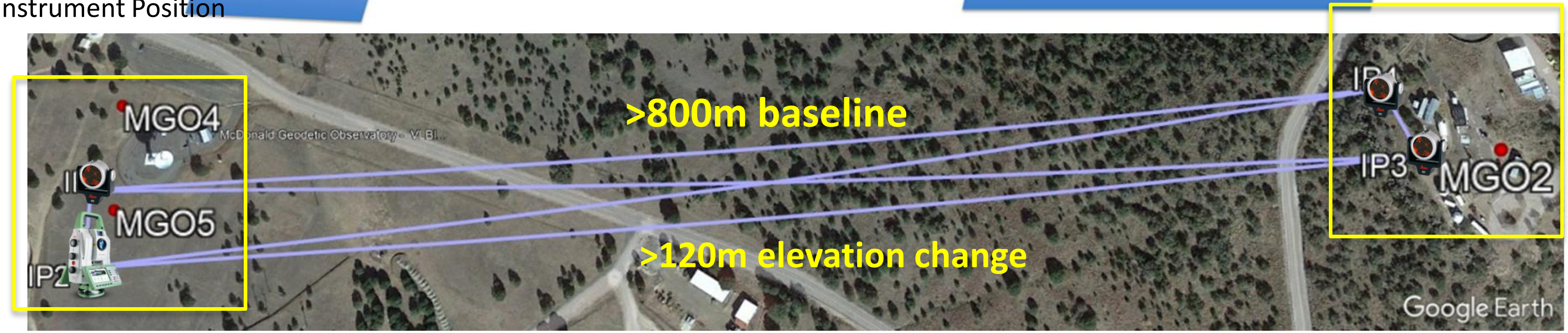
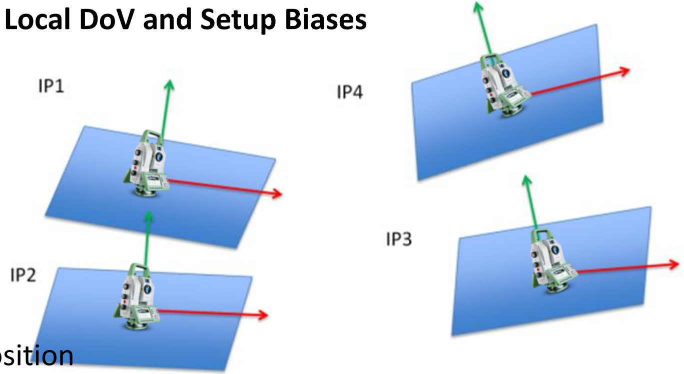


Reciprocal, Cross-braced km-Baseline Observations

Braced Quadrilateral

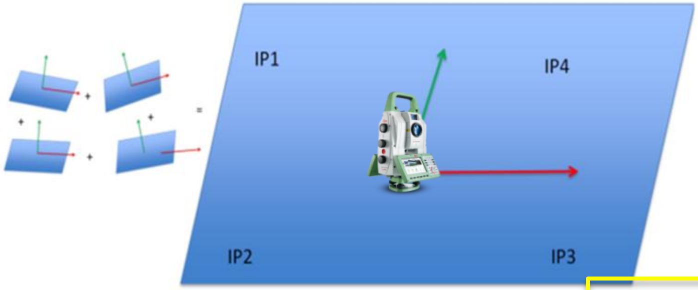
Instrument Positions (IP) in Local Surveys

Local DoV and Setup Biases

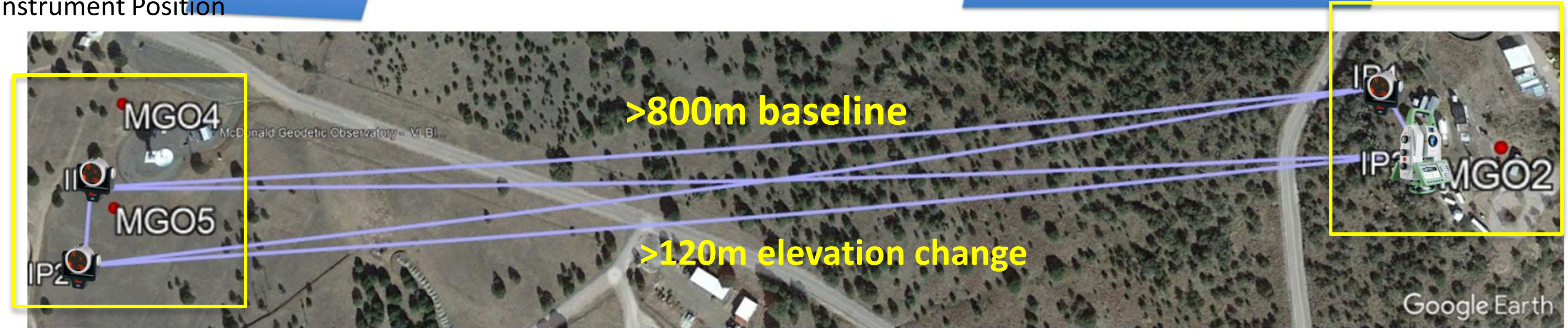


IP Local Frames Combine to Single Frame Survey

via estimated 3-D rotations per IP local frame

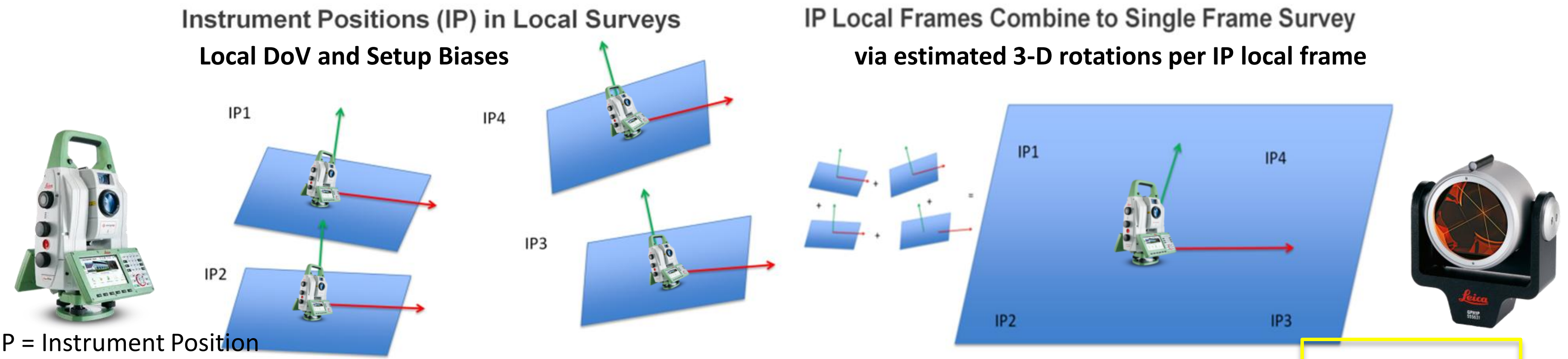


IP = Instrument Position

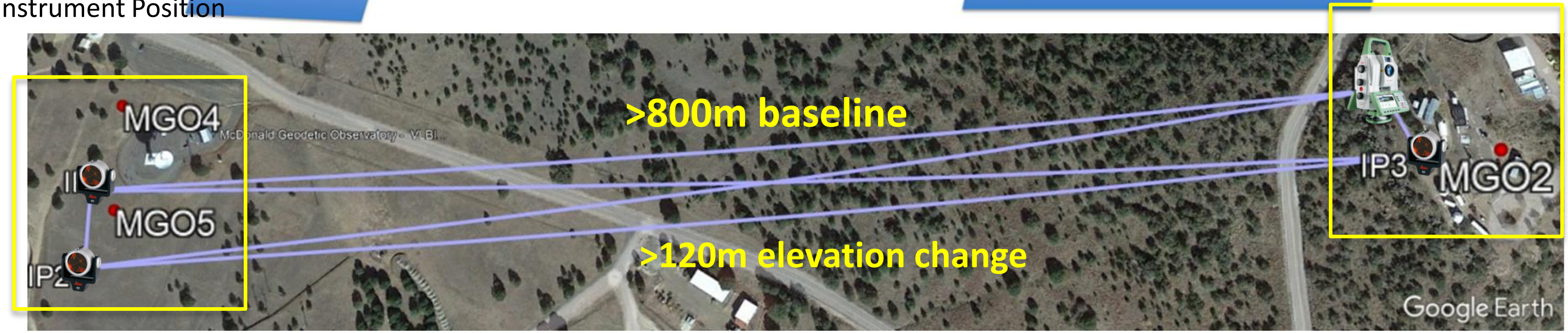


Reciprocal, Cross-braced km-Baseline Observations

Braced Quadrilateral

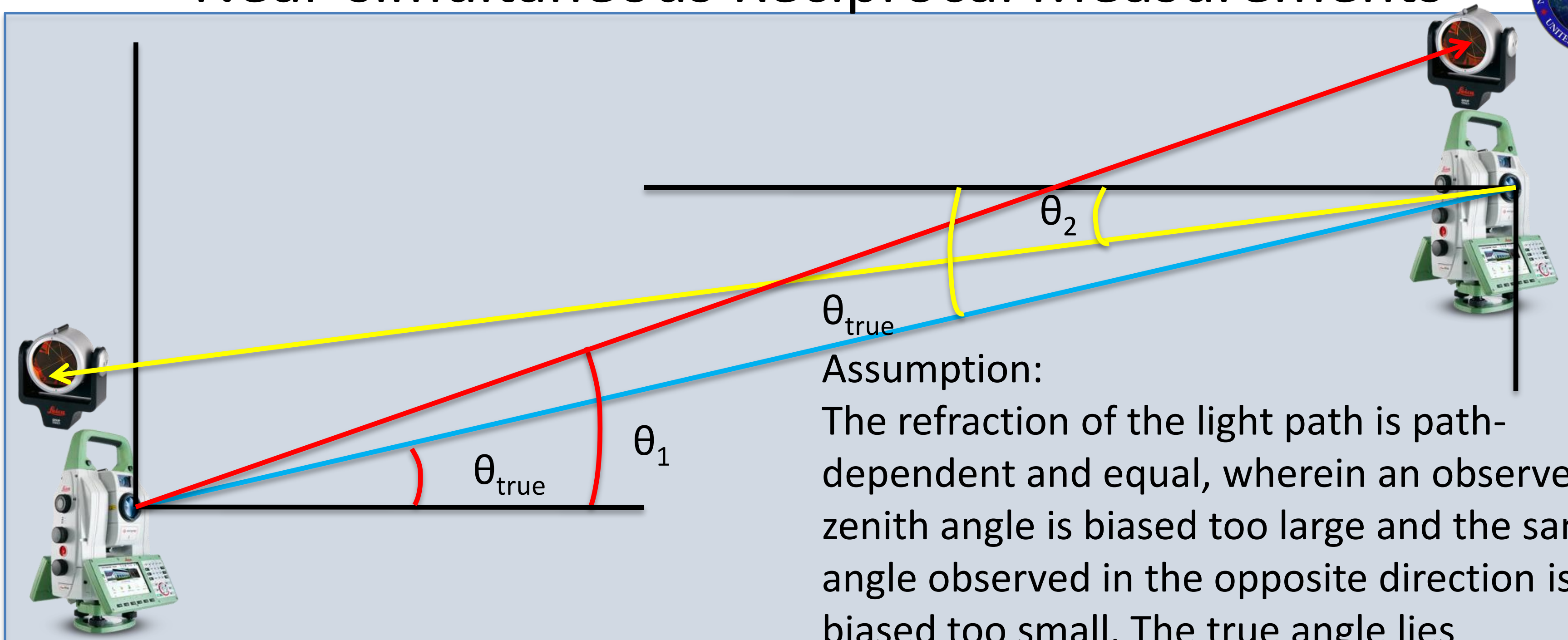


IP = Instrument Position



Reciprocal, Cross-braced km-Baseline Observations

Near-simultaneous Reciprocal Measurements



Elevation Angle = 90deg – Zenith Angle

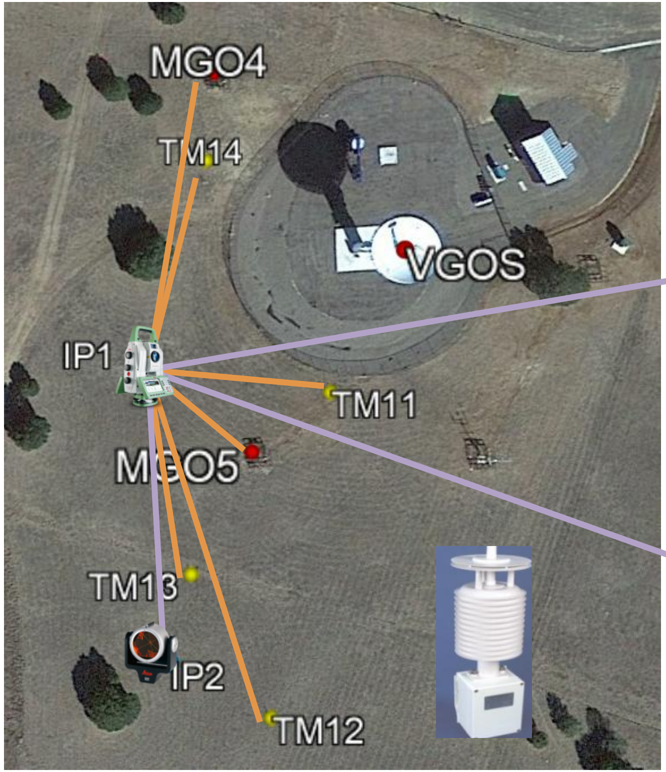
Assumption:

The refraction of the light path is path-dependent and equal, wherein an observed zenith angle is biased too large and the same angle observed in the opposite direction is biased too small. The true angle lies somewhere in between.

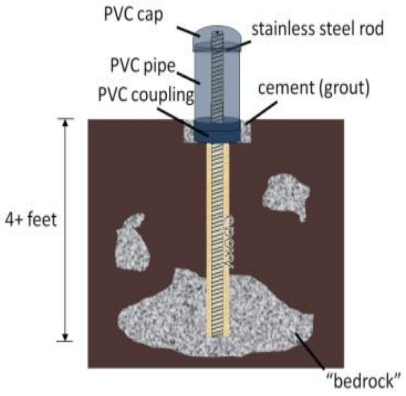
$\theta_1 > \theta_{true} > \theta_2$

Therefore, $\theta_{true} \approx (\theta_1 + \theta_2)/2$

Local Ground Control Networks (LGCN)



- Step 1: Occupy an IP
  - Collect multiple sets of observations of BQ and LGCN, and geodetic stations
  - Simultaneously record weather data
- Step 2: Occupy the next IP



Data Processing

Observations: Raw observations from total station with no internal corrections applied – no atmospheric ppm, no averaging, no scale, no global reference, no curvature

Range	+/- 0.2 millimeters	4 observations per IP-target pair
Zenith Angle	+/- 15 arcseconds	4 observations per IP-target pair
Azimuth Angle	+/- 8 arcseconds	4 observations per IP-target pair

Pre-Processing Steps – manually apply models and corrections to raw observations

Gravitational Loading and Collimation Error Correction - Averaging observations taken with "Forward" and "Reverse" total station orientations

First and Second Velocity Corrections – electronic distance measurement correction for the speed of light	First V Correction to Range: 1ppm = 1mm/km Second V Correction to Range: 1ppb = 1mm/1000km
Wave to Chord Reduction – correcting length of light path due to curvature	Correction to Range: 1ppb

Estimation: In-House Iterative Least Squares Solver – Non-Linear LS Batch Estimator using Gauss-Newton Iteration

Estimated Parameters

XYZ Coordinates for each point in the network	3 x N points = 3N parameters
3 rotation parameters per IP setup	3 x 4 = 12 parameters
Zenith Refraction Bias per IP-IP kilometer baseline	2 Cross-BQ Observations x 4 IP = 8 parameters

A priori: Fix one control point to be the origin of the estimated local frame with tight prior, other parameters are free

Formal Sigmas

1-2 mm in the Up direction

Metrics of Quality

Precision – sub-mm level post-fit residuals and sub-mm repeatability of the survey day to day
Accuracy – mm-level repeatability of LGCN polygon between multiple field campaigns, external validation of GPS ARP local tie polygon with GPS-derived ties
Stability – sub-mm level modeling of LGCN polygon motion via continuous observation
Drift – given baseline model of stability, characterize individual motion of geodetic instruments relative to one another and LGCN polygon

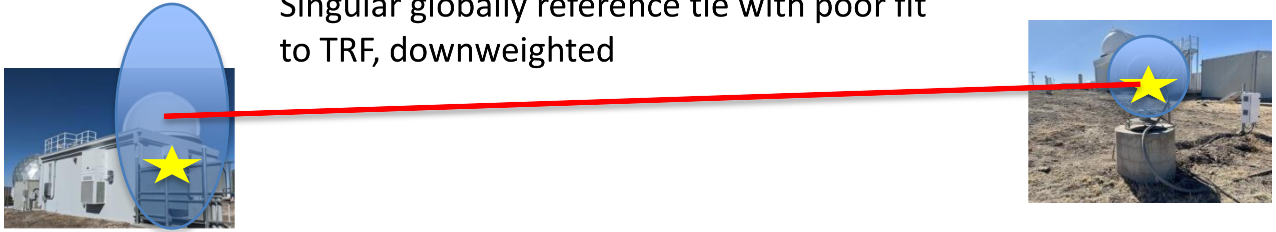
Summary of Local Tie Quality

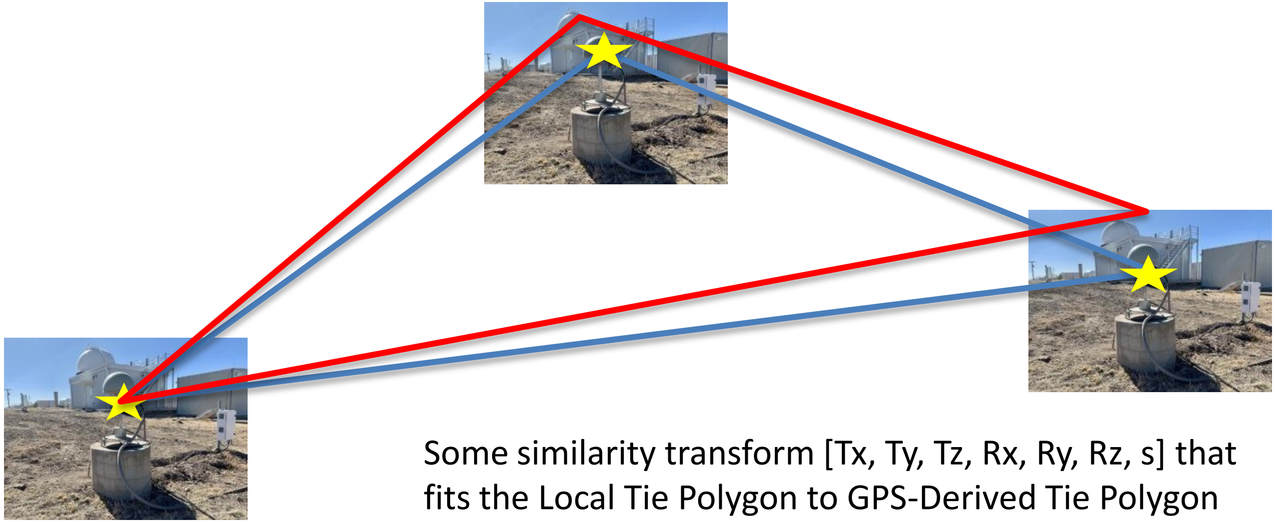
- Survey Campaign Details:
  - May 16-20, 2021 : 2 surveys of LGCN
  - September 15-17, 2021 : 2 surveys of LGCN and GPS stations
  - November 29 – December 2, 2021 : 2 surveys of LGCN and GPS station

Station (Type)	Precision	Accuracy	Stability	Drift
MGO2 (GPS)	Daily: <1.0mm - Scale: <1.0mm	Seasonal: 1-2mm Ext. Valid: 1-2mm - Scale: <1mm	Daily: Sub-mm Seasonal: TBD	TBD
MGO4 (GPS)	Daily: <1.0mm - Scale: <1.0mm	Seasonal: 1-2mm Ext. Valid: 1-2mm - Scale: <1mm	Daily: Sub-mm Seasonal: TBD	TBD
MGO5 (GPS)	Daily: <1.0mm - Scale: <1.0mm	Seasonal: 1-2mm Ext. Valid: <1.0mm - Scale: <1mm	Daily: Sub-mm Seasonal: TBD	TBD

External Validation with Intra-Technique Ties

Singular globally reference tie with poor fit to TRF, downweighted





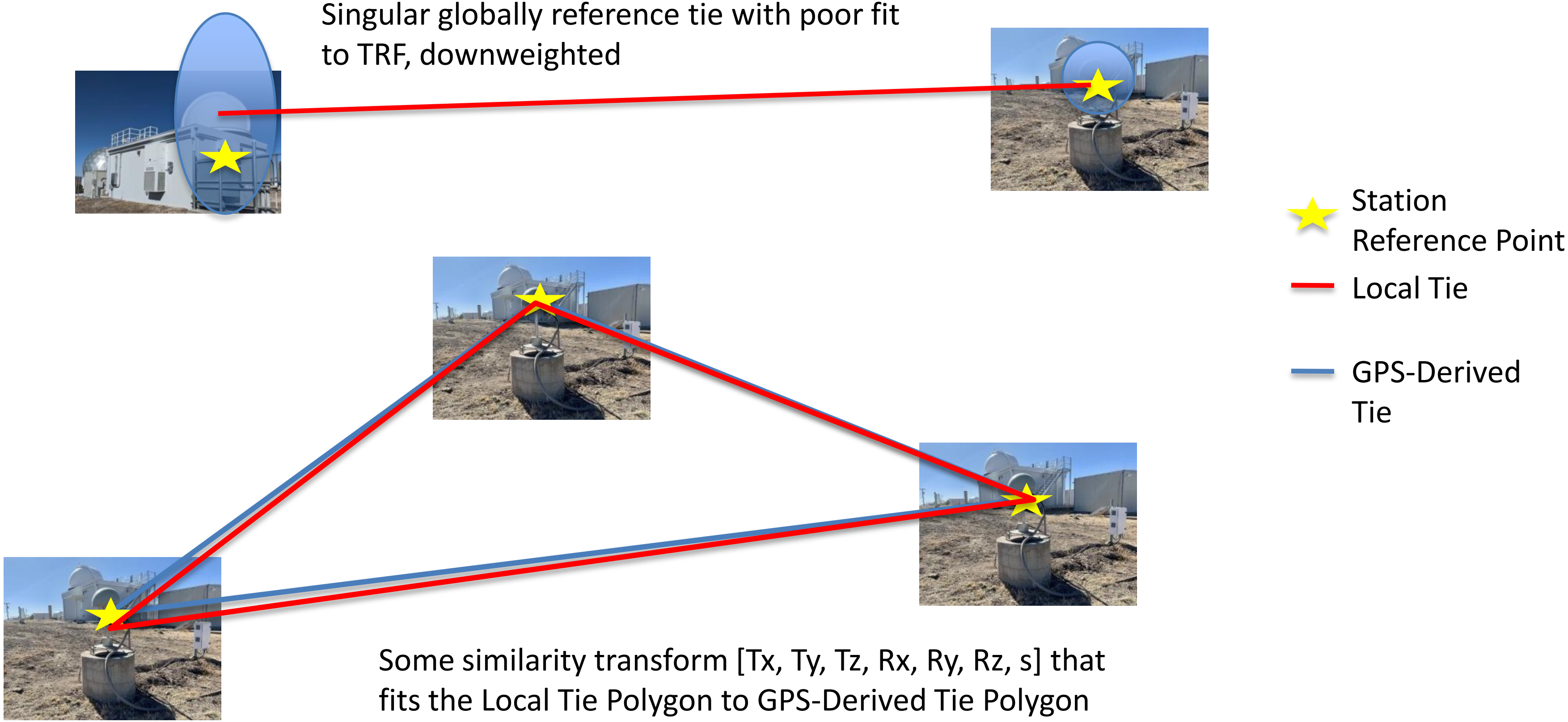
Station Reference Point

Local Tie

GPS-Derived Tie

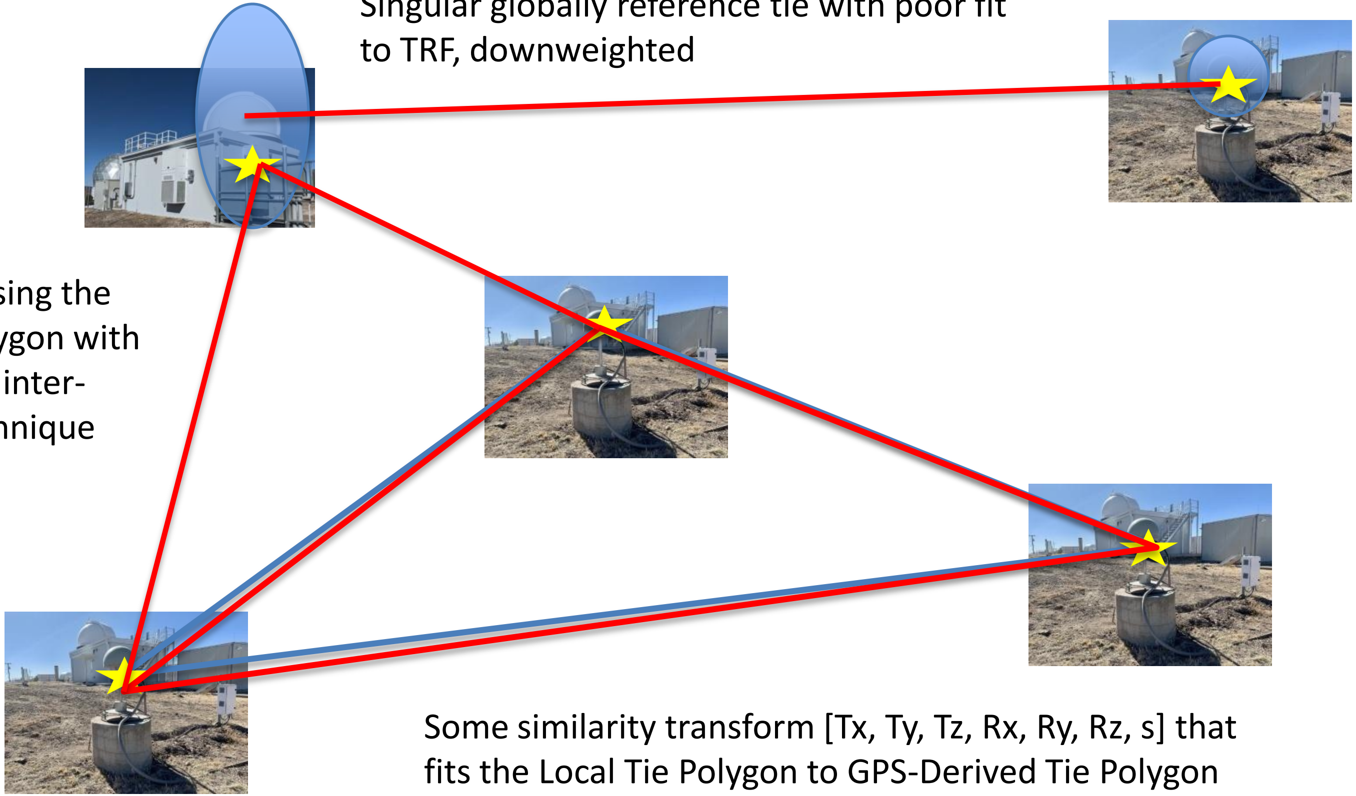
Some similarity transform [Tx, Ty, Tz, Rx, Ry, Rz, s] that fits the Local Tie Polygon to GPS-Derived Tie Polygon

External Validation with Intra-Technique Ties



External Validation with Intra-Technique Ties

Singular globally reference tie with poor fit to TRF, downweighted



Closing the polygon with the inter-technique ties

Station Reference Point

Local Tie

GPS-Derived Tie

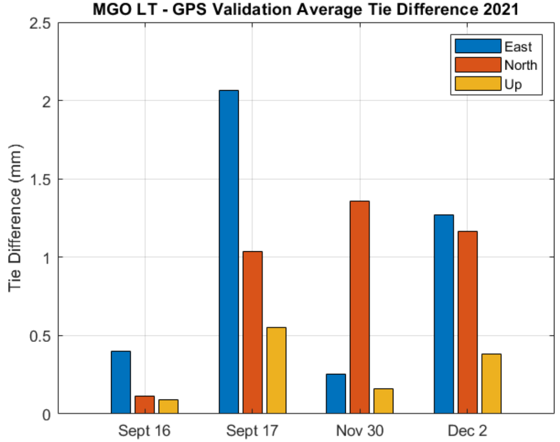
Some similarity transform [Tx, Ty, Tz, Rx, Ry, Rz, s] that fits the Local Tie Polygon to GPS-Derived Tie Polygon

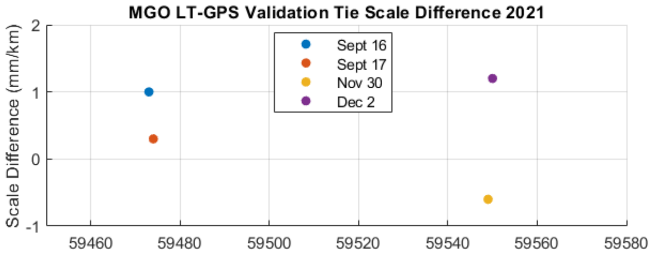
External Validation with GPS

Directly measured Local Ties between GPS ARP from two surveys over a three-month period are compared via 7-parameter Helmert Transform to ties derived from GPS estimated global positions

		Survey on Sept. 16, 2021 compared to Sept. 2021 GPS	Survey on Dec. 2, 2021 compared to Dec. 2021 GPS
Tie Stations	**ENU Metrology Local Tie (m)**	**Tie Difference with GPS-Derived Ties (mm)**	**Tie Difference with GPS-Derived Ties (mm)**
MGO2-MGO4	872.0233 -52.6533 122.9112	-0.3 -0.0 -0.1	0.8 -0.1 0.3
MGO2-MGO5	867.0512 16.6296 121.4022	0.3 0.1 0.1	-1.1 0.8 -0.3
MGO4-MGO5	-4.9721 69.2829 -1.5091	0.6 0.2 0.1	-1.9 1.7 -0.6
Estimated Scale:		1.0mm	-0.1mm

* GPS-Derived Ties: Obtained from Monthly Mean Solution for Sept 2021 and Dec 2021 using Double-Differenced GPS with Ambiguity Fix (DD-A) in ITRF2014





Summary

- The local ties at the kilometer-scale observatory are at the level of accuracy and precision comparable to local ties currently used in the ITRF
  - Ties in this framework are therefore ingestible into realizations of TRF (Require future closure of ties with the VGOS and SGSLR)
- Future Work
  - Add local ties to the VGOS and future SGSLR to the local tie polyhedral network
  - Establish a longer timeseries of local ties
  - Validate inter-technique local ties with technique-derived ties

Recommendations

- Each observatory will require a unique survey framework
- Establish a polygon of local ties for the observatory
  - Ex. Three GNSS stations per multi-technique observatory
- Determine precision and accuracy sigmas with metrics of quality based on repeatability and external validation
- Repeat surveys over multiple campaigns to establish daily, seasonal, annual stability
- Long-term: organization of a permanent international group of professionals for the continuous measurement, analysis, validation, and maintenance of local ties at observatories globally

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  - National Geospatial-Intelligence Agency (NGA), under the NGA Academic Research Program (NARP) NURI (Award Number: HM04762010013)
    - 2020-2022
  - NASA Research Announcement (NRA) NNH16ZDA001N, Research Opportunities in Space and Earth Science (ROSES-2016), Program Element A.48: Space Geodesy Research
    - 2017-2019

Thank you!

Feel free to reach out:
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