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Consistent in-orbit calibration of all-frequency BDS-3 satellite antenna phase centers and their implications for the terrestrial reference frame scale

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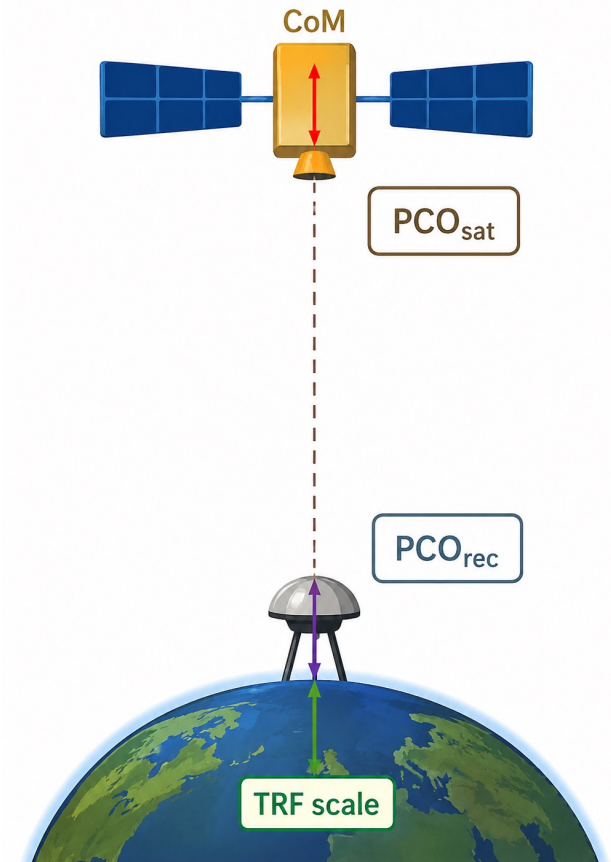


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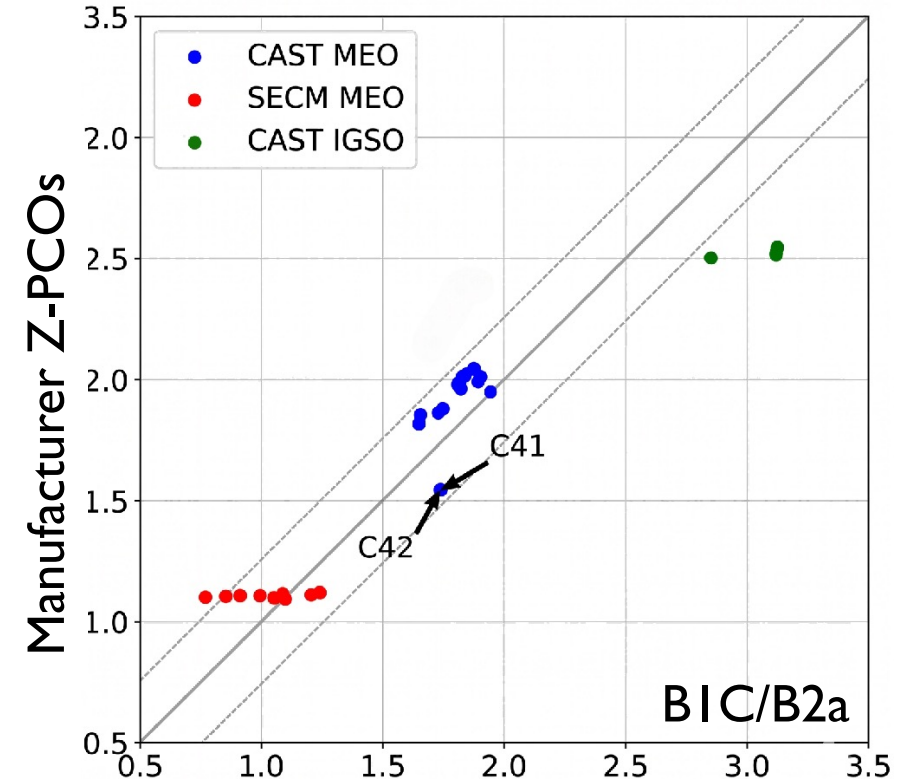
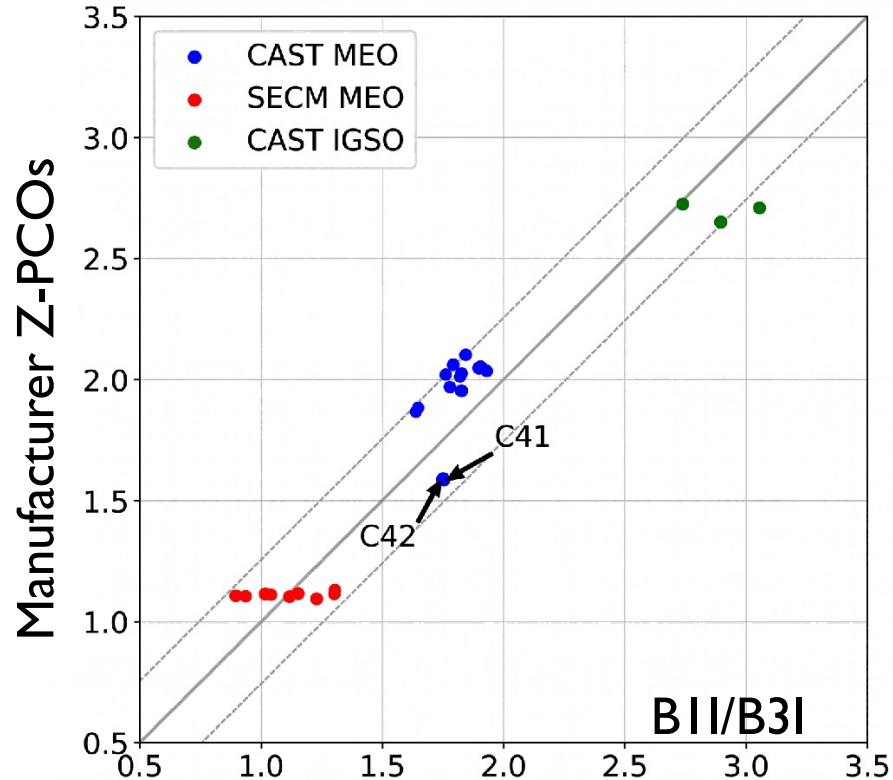
I.1 Background

- Scale determination is essential to terrestrial reference frame realization
- To date (including ITRF2020), the ITRF scale has been solely defined by VLBI and SLR
- GNSS cannot yet contribute as satellite/receiver antenna phase center offsets (PCOs) remain insufficiently known
- Satellite PCO is a 3-D vector (center of mass $\rightarrow$ mean phase center) with horizontal (XY) and vertical (Z) components
- Z-PCO strongly correlates with station height and frame scale (approximately linear)



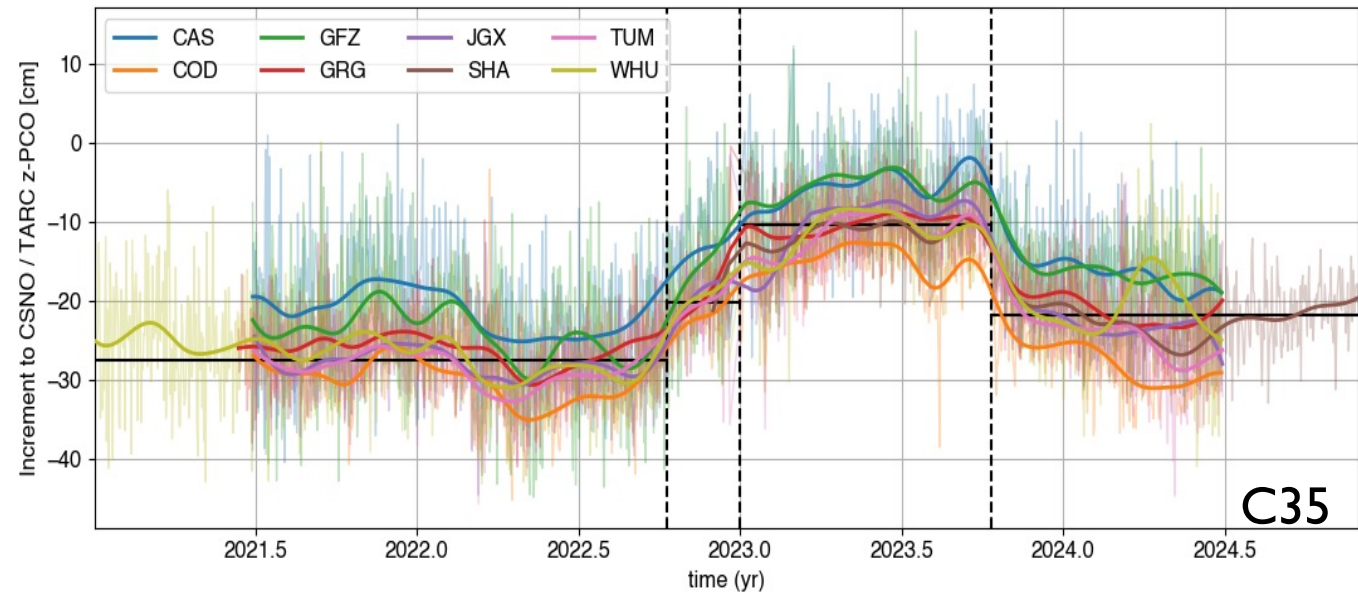
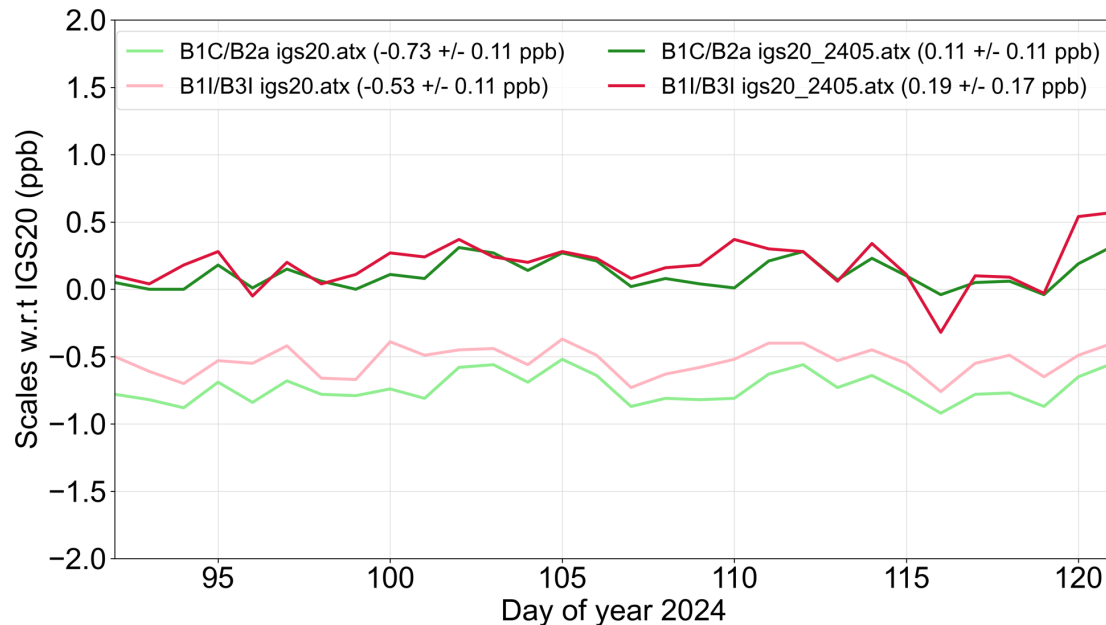
I.2 BDS3 antenna PCO status & challenges

- BDS3 in igs20.atx: manufacturer values from CSNO – not aligned to IGS20
- Manufacturer Z-PCOs vs. in-orbit estimated Z-PCOs:
 - C41/C42 → differences of 30–40 cm
 - Average offset ≈ 10 cm → scale bias up to 0.7 ppb w.r.t. IGS20



I.3 IGS BDS3 PCOs: Current Results

- IGS 2024–2025 campaign (8 ACs)
- In-orbit calibrated IGS20-2405 (aligned with B1C/B2a and B1I/B3I signals only)
- C35, C43, C44: 10–20 cm drifts/jumps identified
- Piecewise Z-PCOs modeling for C35, C43, C44 in igs20_2405.atx



Ref: https://elib.dlr.de/216593/1/IAG_2025_BDSant.pdf

I.4 Limitation & research goal

- IGS approach for obtaining frequency-specific PCO
 - BI PCO is fixed to ground values
 - B2a & B3I PCOs are then derived from B1C/B2a & B1I/B3I
 - B2b & B2ab PCOs are assumed identical to the derived B2a PCO
- Limitation: What if arbitrary combinations of signal frequencies for PPP?
 - Baseline pairs, e.g.. B1C/B2a & B1I/B3I ✓
 - Arbitrary pairs, e.g., B1C/B3I & B1I/B2a & B1C/B2b etc. ✗
- Therefore, the goal of this study
 - Align all-frequency BDS-3 PCOs with IGS20
 - Keep consistency among all arbitrary frequency combinations

2.1 Method

- Fix B1C & B2a PCOs to IGS in-orbit calibrated values (GPS week 2405)
- Estimate PCOs of other frequencies **via uncombined network analysis**

- Our PCOs estimates absorb a frequency-dependent bias in blue ($k \geq 3$)

$$\widehat{PCO}_k = \widetilde{PCO}_k - \gamma_k \beta_{12} (\delta PCO_1 - \delta PCO_2)$$

- IGS B1C & B2a PCOs can be expressed analogously as ($k \leq 2$)

$$PCO_{k,IGS} = \widetilde{PCO}_k - \gamma_k \beta_{12} (\delta PCO_1 - \delta PCO_2)$$

$\widehat{PCO}$: estimated PCOs

$\widetilde{PCO}$: theoretical true values aligned with IGS20

δPCO : IGS B1C & B2a corrections w.r.t. true values

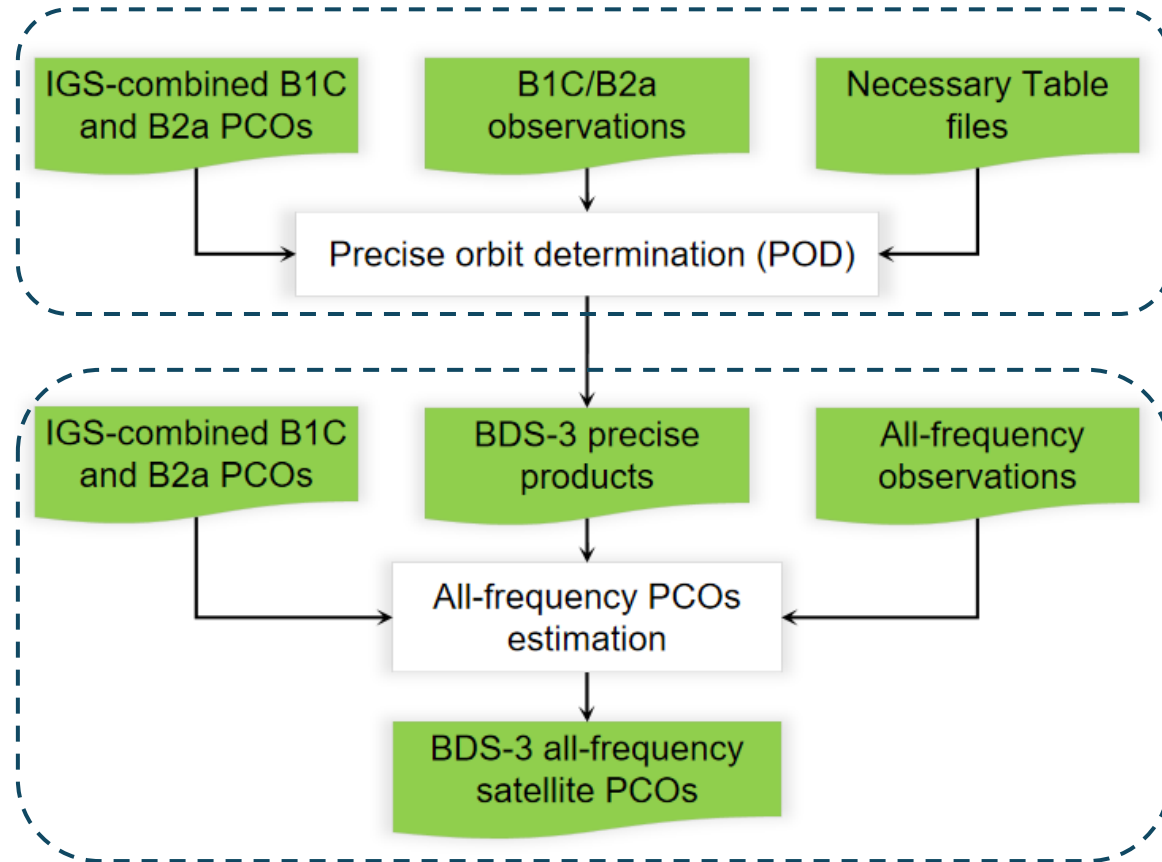
β_{12} : ionosphere-free combination coefficient

γ_k : scaling factor $(f_1/f_k)^2$

$$-\gamma_k \beta_{12} (\delta PCO_1 - \delta PCO_2)$$

- Property: inversely proportional to the square of frequency
- **Mitigation (no panic!)**
 - ✓ ionosphere-free model: the bias is naturally canceled
 - ✓ uncombined model: the bias is absorbed by ionospheric parameters
- Outcome: frequency-specific PCOs are compatible among **all arbitrary frequency combination**

2.2 Flowchart



BDS3 all-frequency PCO estimation workflow

BDS3 satellite precision product generation strategy

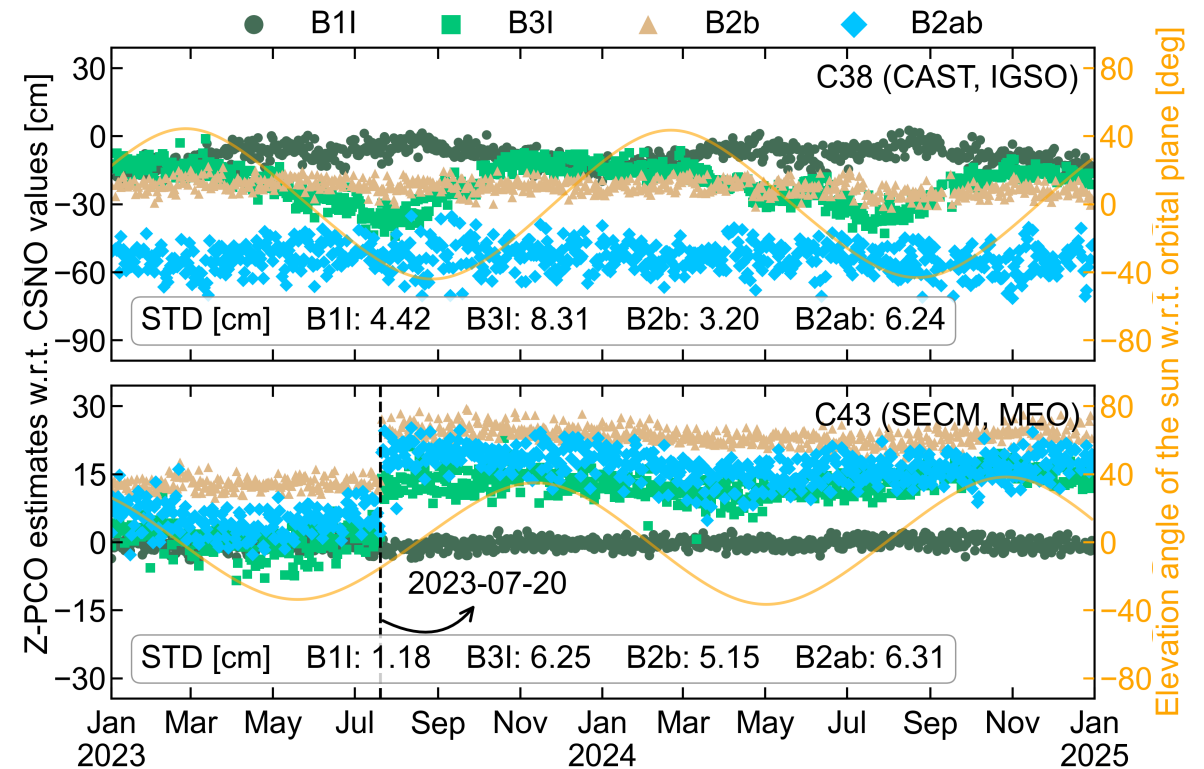
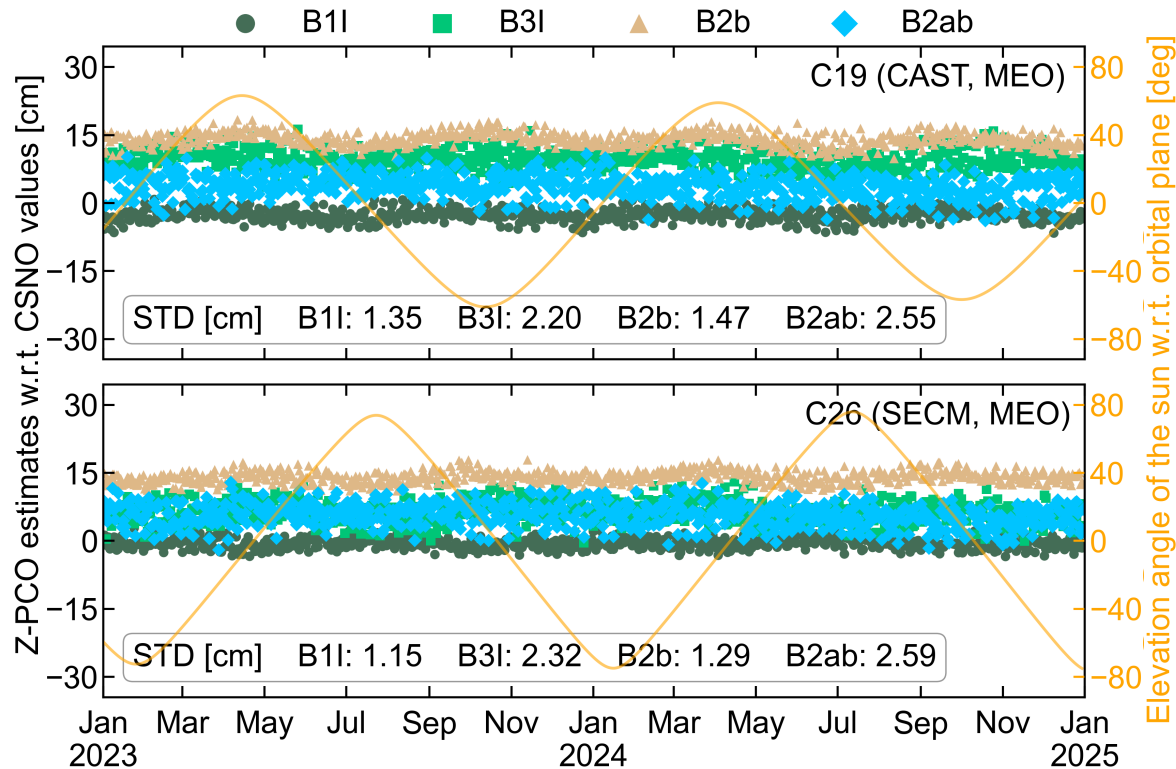
Item	Processing Strategy
System	GPS+BDS3
Observations	Undifferenced ionosphere-free; L1/L2; B1C/B2a
Time span	2023/001-2024/366
Antenna	igs20_2405.atx
SRP	ECOM2

BDS3 all-frequency satellite PCO estimation strategy

Item	Processing Strategy
System	BDS3
Observations	Uncombined; B1C/B1I/B2a/B2b/B2ab/B3I
Satellite PCO	Z-PCO estimated as constant
Coordinates	Fixed to IGS weekly solutions
Ionosphere	Estimated as random walk parameters

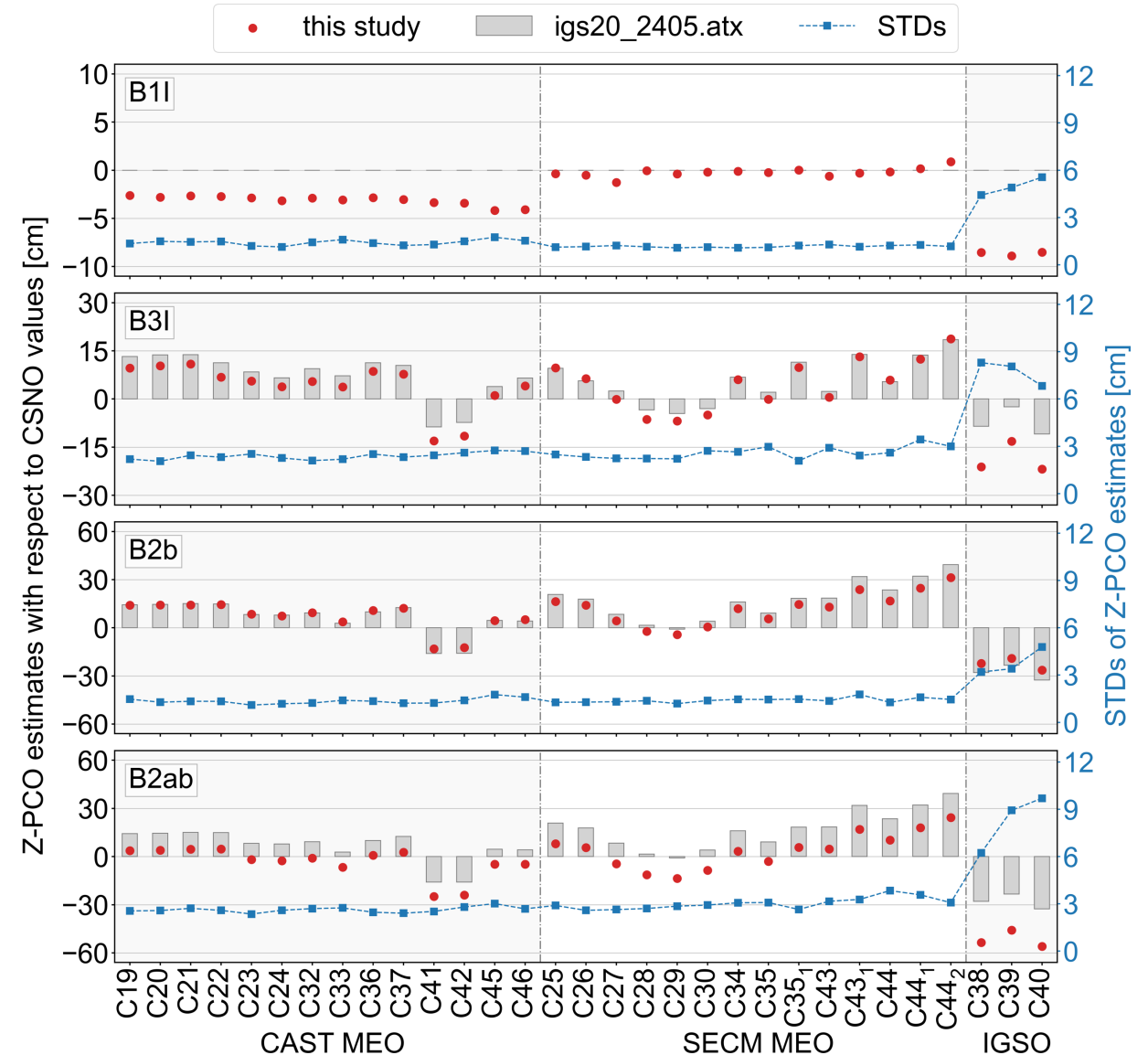
3.1 BDS3 satellite PCO time series

- Z-PCO estimates are generally stable: MEO 1–3 cm, IGSO 4–8 cm (std)
- C43 show a segmentation around 20 July 2023 (IGS piecewise B1C/B2a input)
- IGSO dispersion exceeds MEO



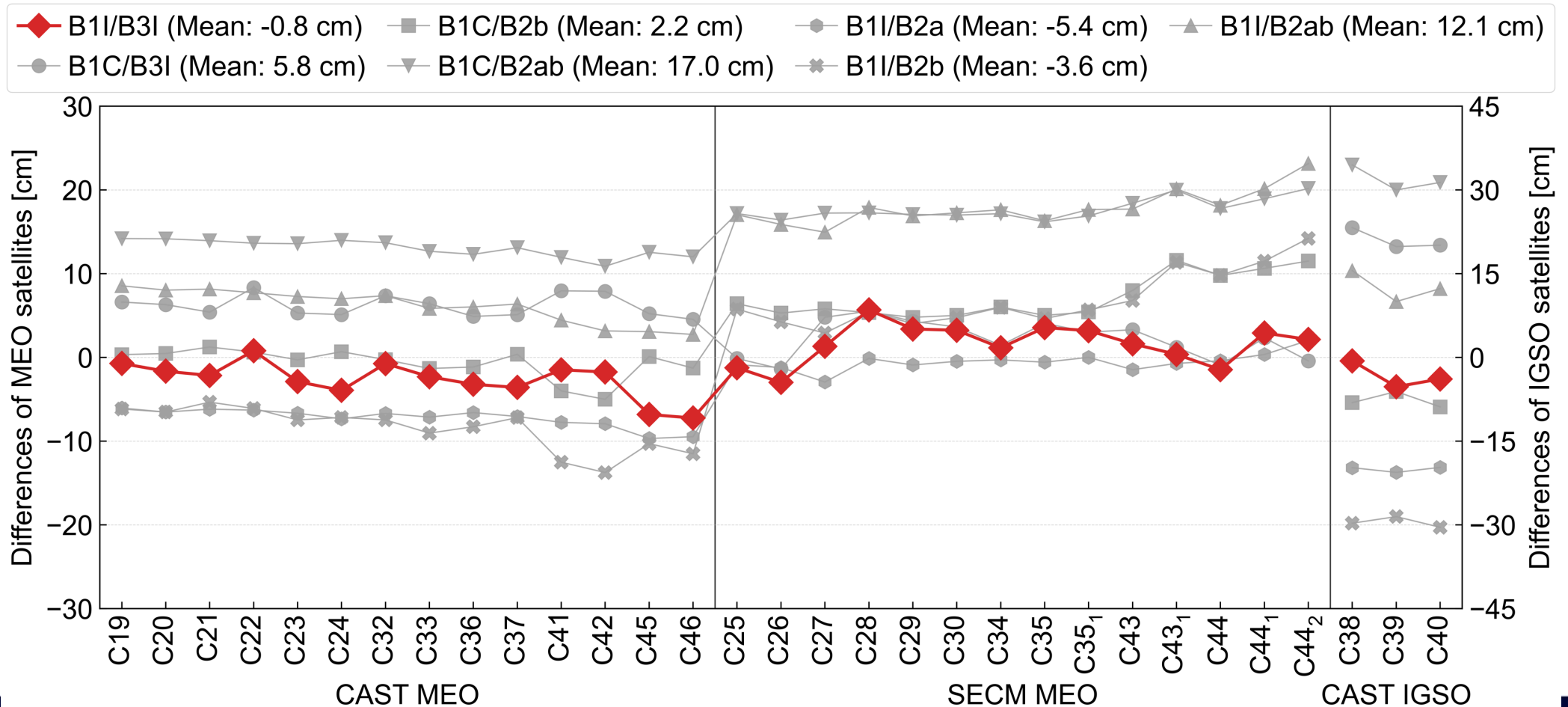
3.2 BDS3 satellite frequency-specific PCO estimates

- CAST MEO
 - frequency-specific offsets vs. CSNO
 - C41/C42: larger outliers
 - systematic offsets vs. *igs20_2405.atx*
- SECM MEO
 - B1I matches CSNO well
 - C35/C43/C44 display ~10 cm jumps
- IGSO: offsets reach much larger values
- Intrinsic errors (STDs): $B1I \approx B2b < B3I$



3.3 Ionosphere-free PCO comparison with igs20_2405

- B1I/B3I: excellent agreement with igs20_2405.atx (mean difference ≈ -0.8 cm)
- Other combinations: systematic offsets (several cm to over 10 cm)



3.4 TRF scale and positioning performance

- Estimated PCOs calibrate CSNO scale bias **to near zero**
- Scale discrepancy of igs20_2405.atx reduced from **0.4 ppb to 0.1 ppb** using our estimated PCOs
- Comparable horizontal and slightly better vertical positioning precisions

Freq. pairs	CSNO		igs20_2405.atx		this study	
	scale(ppb)	E/N/U (mm)	scale (ppb)	E/N/U (mm)	scale (ppb)	E/N/U (mm)
B1C/B2a	-0.96	2.35/3.43/8.22	0.05	2.39/3.41/5.45	0.05	2.32/3.51/5.15
B1C/B2b	-0.87	2.33/3.54/7.65	0.14	2.31/3.53/5.47		
B1C/B3I	-0.65	2.43/3.56/7.31	0.27	2.42/3.55/6.67	0.03	2.43/3.51/6.06
B1I/B2a	-0.97	2.76/3.69/8.74	-0.13	2.72/3.64/6.05	0.08	2.68/3.66/5.81
B1I/B2b	-0.89	2.74/3.78/8.01	-0.07	2.72/3.76/6.16	0.06	2.72/3.76/6.10
B1I/B3I	-0.74	2.91/3.79/8.38	0.11	2.86/3.74/7.22	0.13	2.85/3.75/7.26

Note: IGS weekly solutions are used as reference

4 Summary

- Consistent all-frequency BDS3 satellite PCOs aligned with the IGS20 frame using an uncombined model with the IGS-combined B1C/B2a PCOs as reference
- The estimated Z-PCOs are generally stable, while several satellites (e.g., C35/C43/C44) exhibit noticeable temporal variations and require piecewise modeling
- Compared with the existing CSNO and igs20_2405.atx models, our PCOs significantly reduce TRF scale biases and improve inter-frequency consistency for arbitrary combinations
- Positioning validation demonstrates that the estimated all-frequency PCO model achieves the best vertical positioning performance among the tested models



Thanks for your attention!

All-frequency satellite PCO products of this study in the ANTEX format are available at:

<https://bdspride.com>

Impact of satellite antenna PCO on the Terrestrial Reference (TRF) frame scale

