Quality assessment of the BeiDou-3 phase center offset calibrations in terms of the realization of the terrestrial reference frame scale

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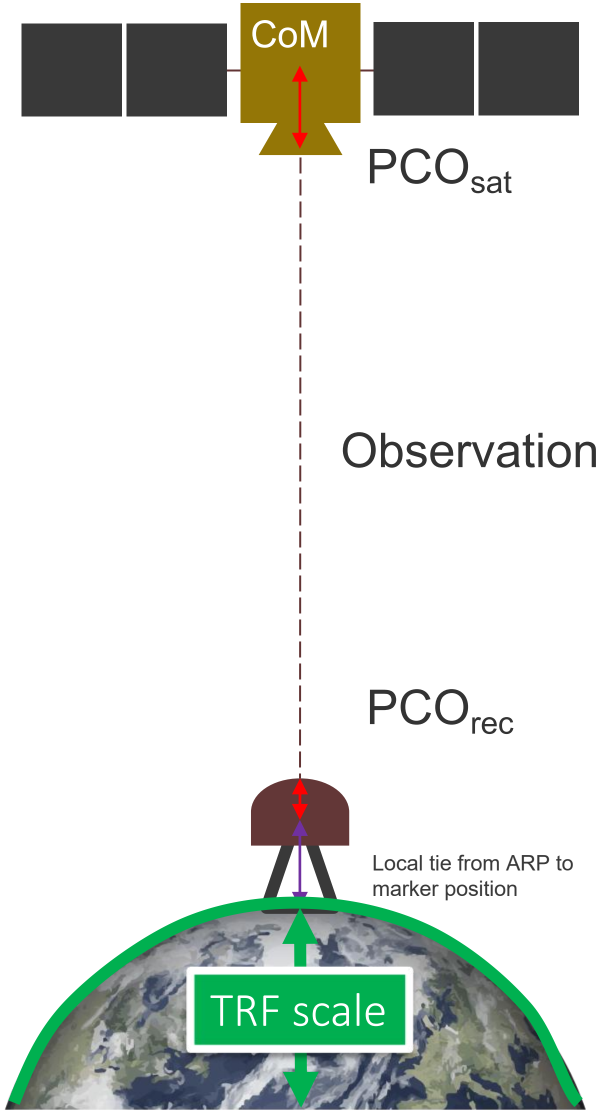
Realization of ITRF scale

- One important aspect when realizing a reference frame is the realization of the scale.
- Up to now (including ITRF2020), the scale of the ITRF **is defined by Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR).**
- A priori unknown satellite (and partly receiver) antenna phase center offsets (PCO) prevented the use of GNSS for the scale estimation.
- The phase center offset (PCO) is a vector between the antenna phase center and a well-defined physical reference point. The PCO is defined by two horizontal components, i.e., PCO-x and PCO-y, and one vertical component, i.e., PCO-z, following the spacecraft axis definitions. In principle, the information about the PCO in the z direction (PCO-z) is essential, as this component, ideally pointing toward the center of the earth, is in a straight-line relationship with the reference frame scale.

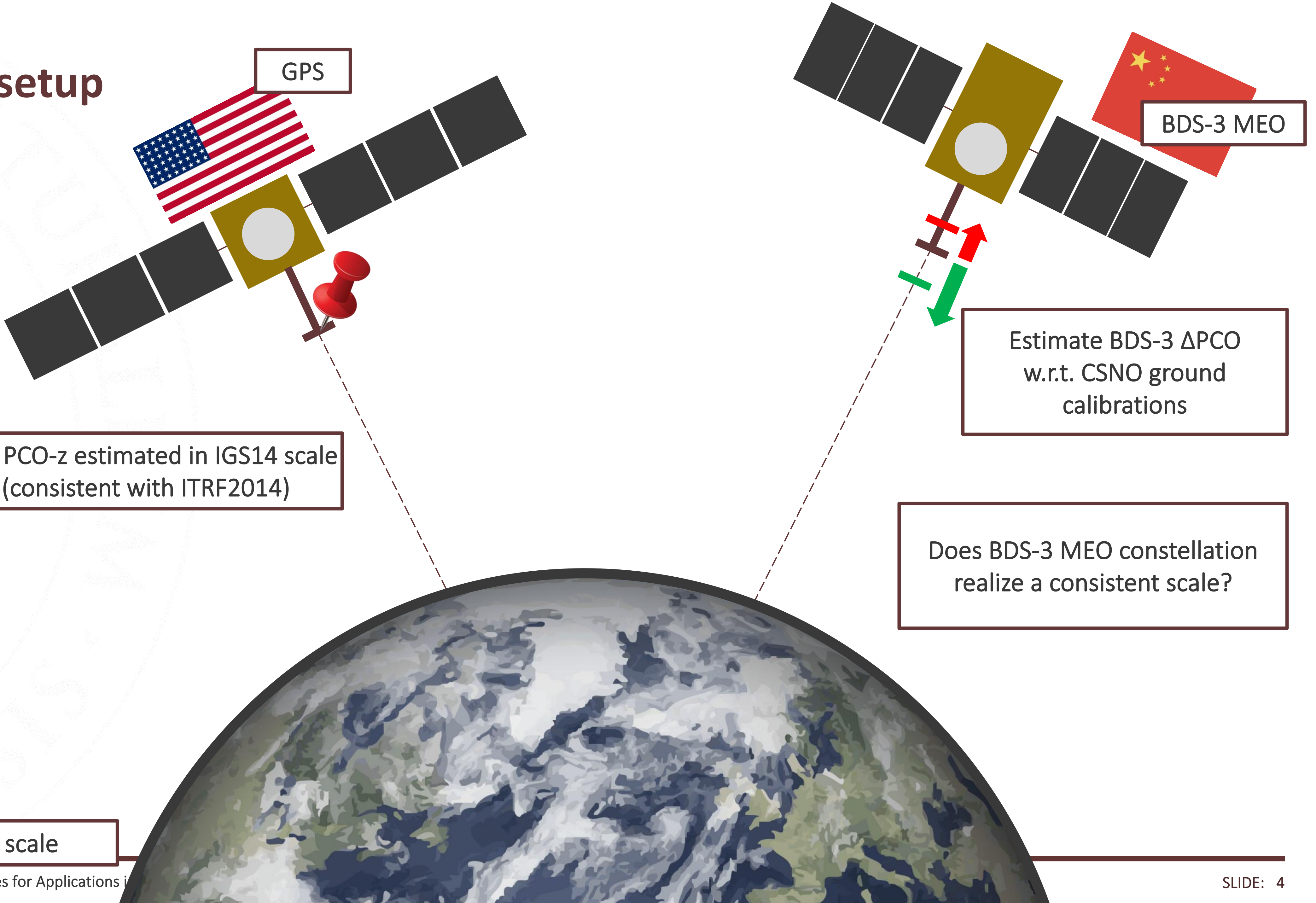


Realization of the TRF Scale with GNSS

- The European GNSS Agency (GSA) released as the first global system provider the satellite antenna calibrations of the Galileo satellites (PCO_{SAT}).
- In 2019 Geo++ published a set of robot calibrations for the ground antennas covering a wide range of multi-GNSS signal frequencies, including all the GPS, GLONASS, Galileo, BeiDou, and QZSS frequencies (Wübbena et al. 2019).
- Villiger et al. (2020) reported that the Galileo-based scale difference w.r.t. ITRF2014 is 1.4 parts per billion (ppb)
- Next GNSS providers released calibrations
- Disclosed BeiDou (CSNO) and GPS BLOCK IIIA PCO values allow comparisons between different GNSS
    - **What is the potential contribution of BeiDou to the realization of the terrestrial reference frame scale? <u>(BDS-3 MEO only)</u>**

	PCO_{SAT}	PCO_{REC}
GPS (BLOCK I-II)	Estimates	Calibration
GPS (BLOCK III)	Calibration	Calibration
GLONASS	Estimates	Calibration
Galileo	Calibration	Calibration
BeiDou	Calibration	Calibration
QZSS	Calibration	Calibration

Experiment setup



GPS PCO-z estimated in IGS14 scale (consistent with ITRF2014)

Estimate BDS-3 ΔPCO w.r.t. CSNO ground calibrations

Does BDS-3 MEO constellation realize a consistent scale?

Analysis 1

ITRF14/IGS14 scale

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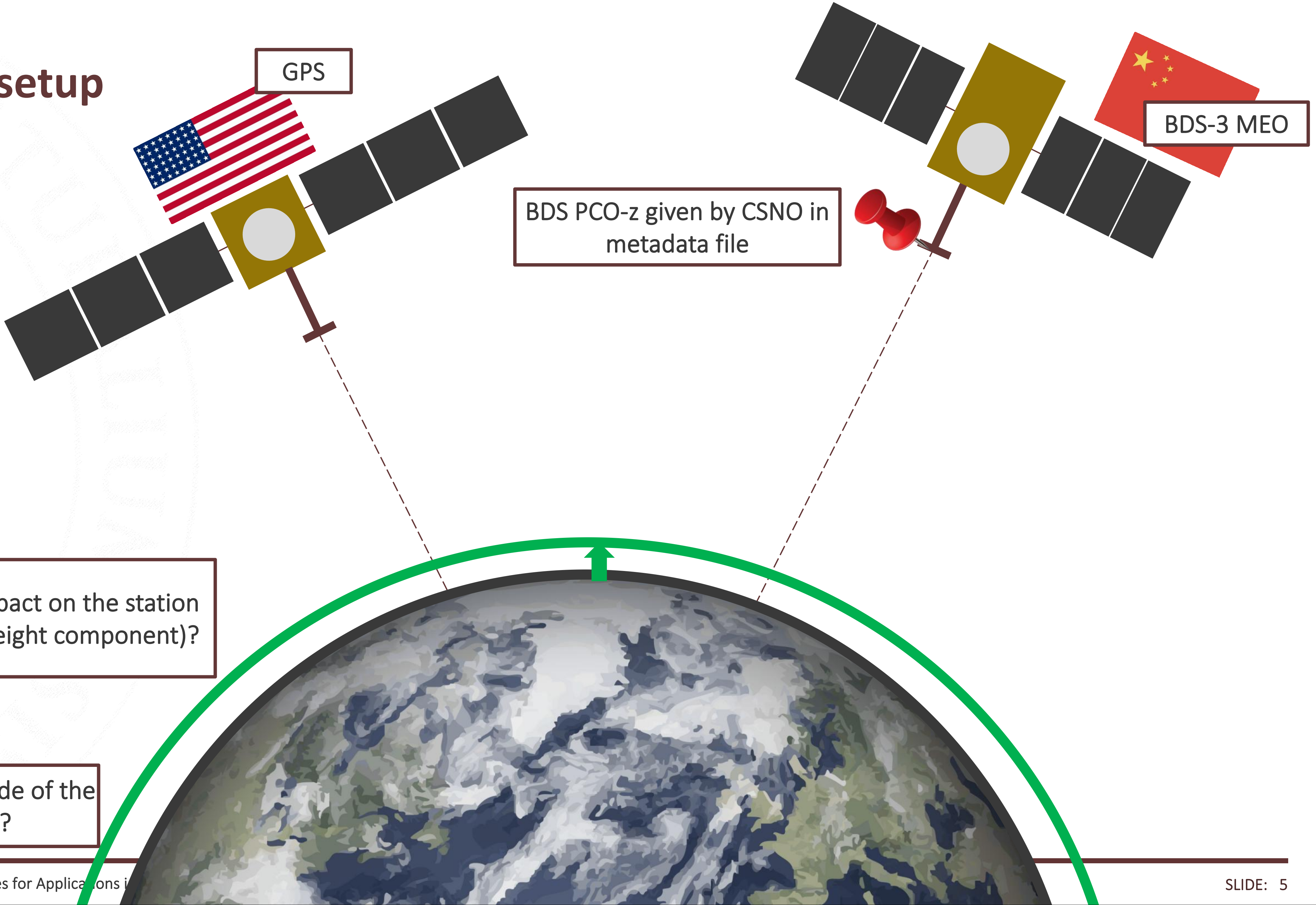
Experiment setup



GPS

BDS-3 MEO

BDS PCO-z given by CSNO in metadata file

Analysis 2

What is the impact on the station coordinates (height component)?

What is the magnitude of the scale change?

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Experiment setup

- GPS+BDS-3 global network processing
- covering the whole year of 2021
- based on the observations collected by up to 145 globally distributed ground stations from the IGS multi-GNSS network (Montenbruck et al. 2017)
- The processing was performed using the NAPEOS software (Springer 2009)

- The analysis consists of solutions, which differ in:
  - **SRP modeling** - proper modeling of the SRP is a prerequisite for an accurate determination of PCO values (Steigenberger et al. 2016).
  - **Frequencies** - aiming to verify whether the scale realization is consistent for different pairs of frequencies forming an ionosphere-free linear combination.

Constant processing feature	Strategy
Satellites	GPS and BDS-3 MEO
Observables	Zero-differenced approach using the ionosphere-free linear combination
Data period	2021
Sampling rate	5 min
Elevation cutoff angle	10°
Elevation-dependent weighting	$\sigma = \sigma_0 \sin \epsilon$
Ambiguity resolution	For GPS and BDS using the Melbourne-Wübbena approach
Troposphere a priori model	Global Pressure and Temperature (GPT) model (Boehm et al. 2007)
Troposphere mapping function	Global Mapping Function (GMF; Boehm et al. 2006)
Receiver antenna calibrations	igsR3_2077.atx
Satellite antenna calibrations	GPS: igs14_2178.atx (Rebischung and Schmid 2016) BDS-3: from CSNO metadata (CSNO 2019b)
Earth albedo	numerical model according to Rodriguez-Solano et al. (2012b)
Transmit thrust	applied consistently with IGS MGEX metadata
Variable processing features	**Strategy**
Solar radiation pressure (SRP) modeling	Next slides
Frequency pairs	GPS: L1 C/A, L2 P(Y) **BDS: B1I/B3I (B1B3) and B1C/B2a (B1B2)**

Experiment setup - tracking network

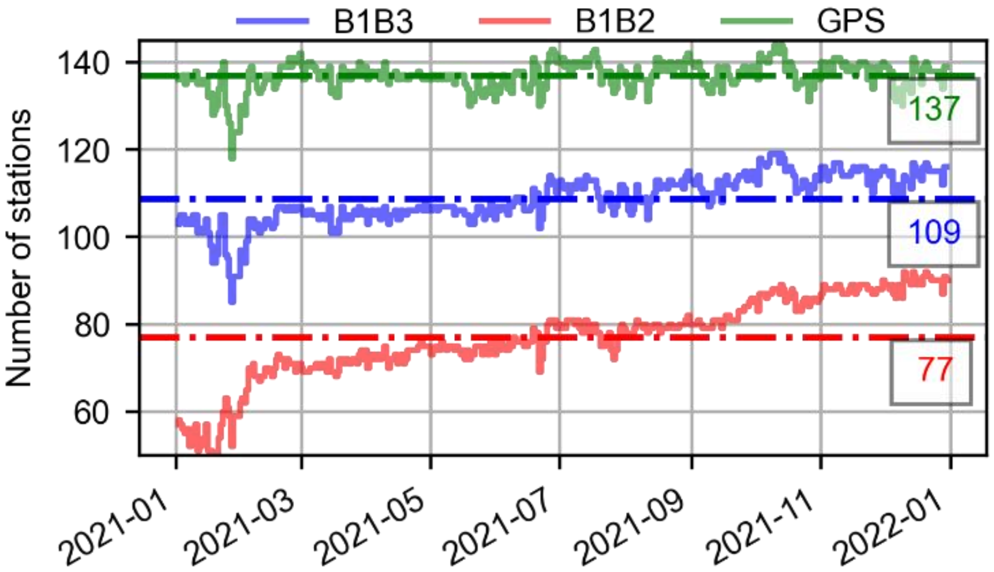
Two main issues remain nowadays in tracking BDS-3 satellites.

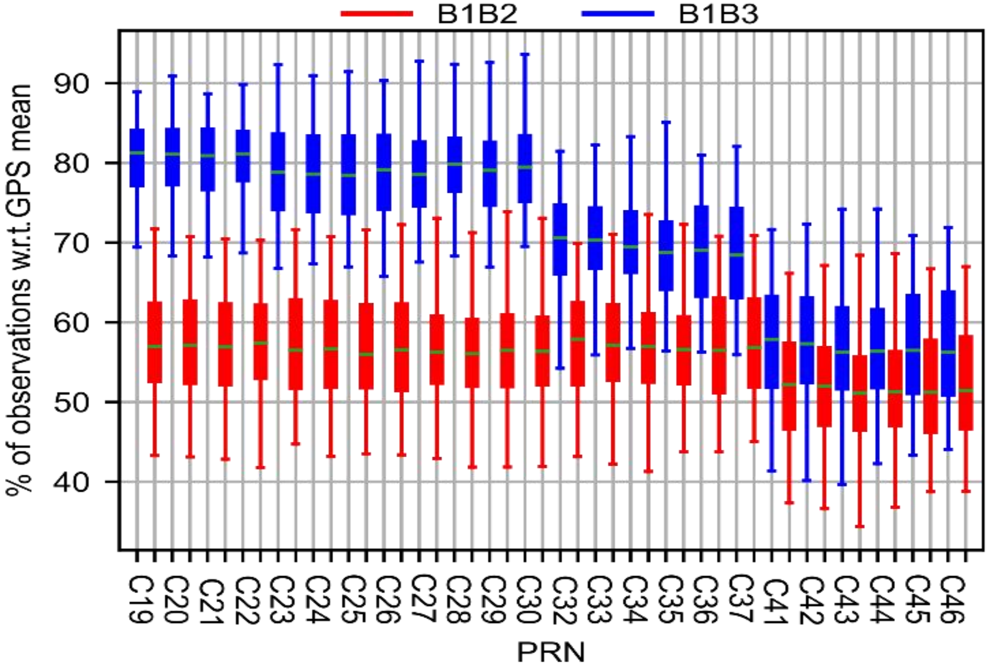
- Despite a wide range of frequencies and signals transmitted by BDS satellites, not all of them are supported by the receivers.

Network of 145 stations, all of which track GPS satellites.
In 2021, the network includes on average **109 and 77 stations tracking BDS-3 B1I/B3I and B1C/B2a signal pairs, respectively.**

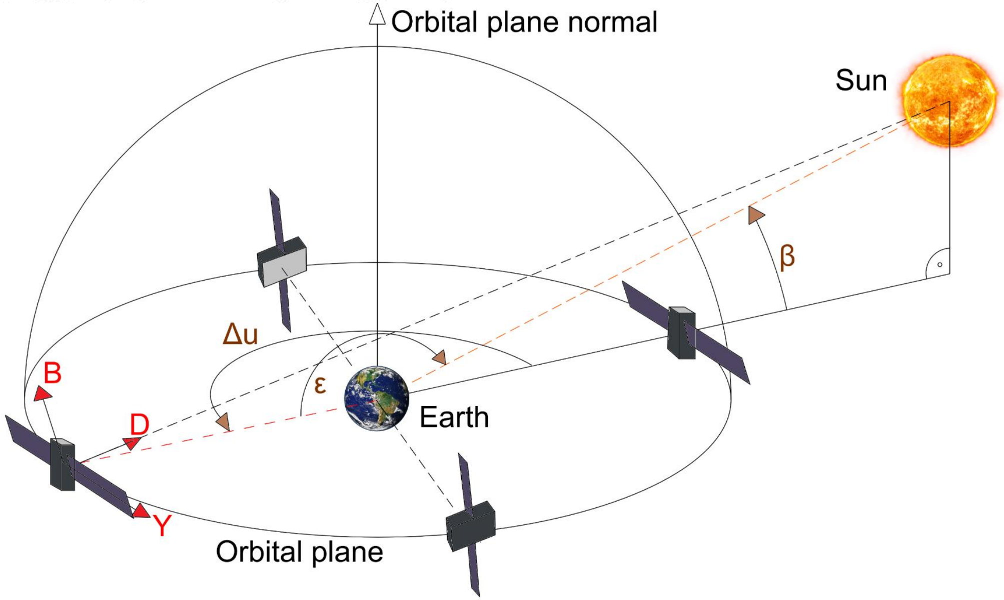
Until the 6th of February 2021 the number of stations supporting B1C/B2a tracking in the network was too poor to deliver solutions of the comparable quality to the rest of the year.

- Not all deployed BDS-3 satellites can be tracked by an equal number of receivers, mainly due to the limitation of tracking channels or outdated firmware.



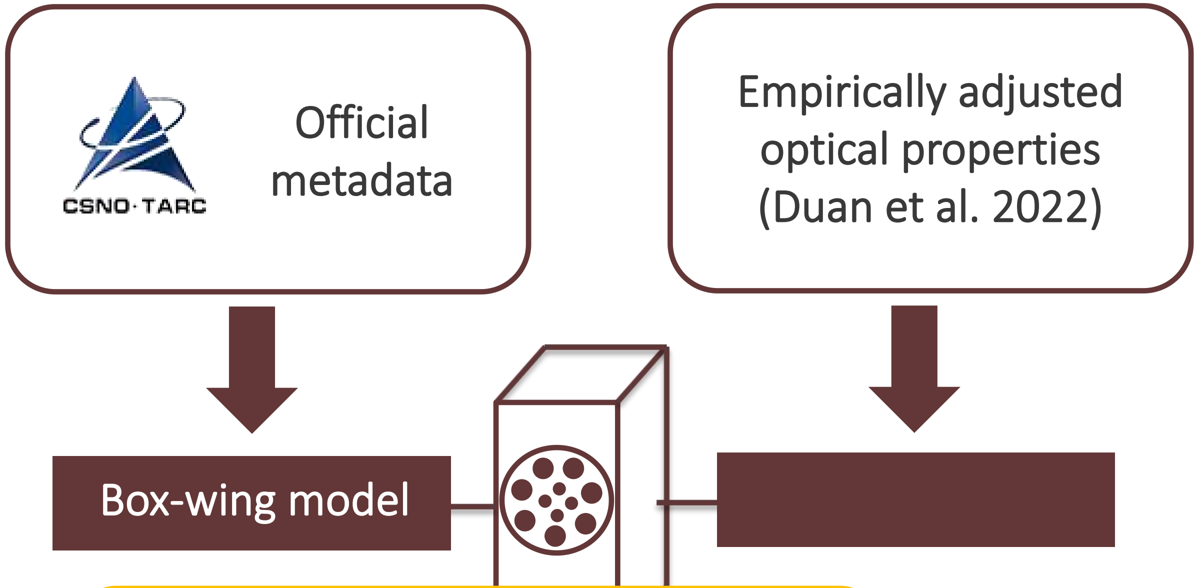


Solutions: SRP modeling



$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + D_{2C}\cos 2\Delta u + D_{2S}\sin 2\Delta u \\ Y_0 \\ B_0 + B_{1C}\cos\Delta u + B_{1S}\sin\Delta u \end{bmatrix}$$

ECOM2 – Extended Empirical CODE Orbit Model (Arnold et al. 2015)



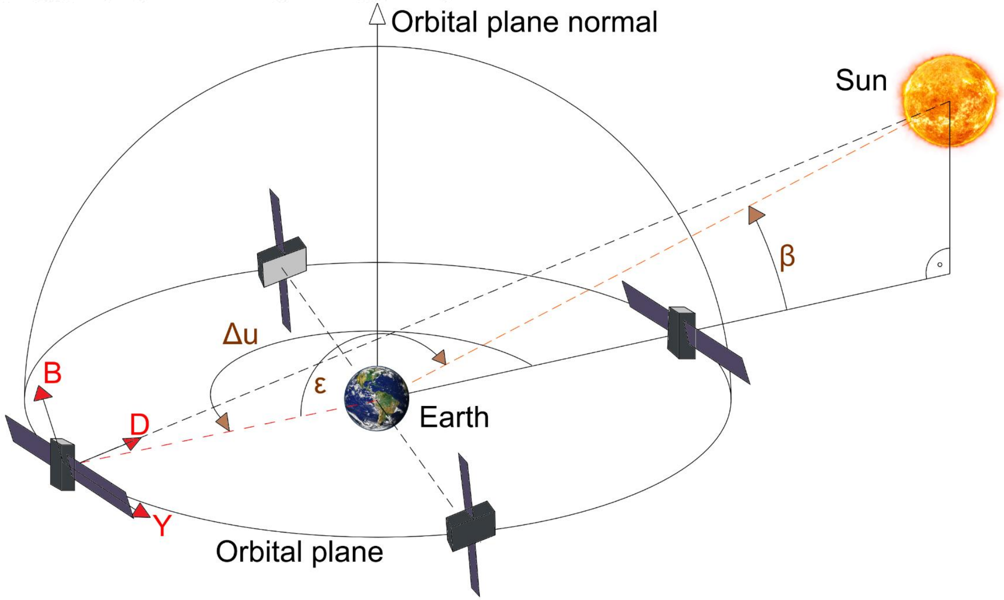
CSNO·TARC Official metadata

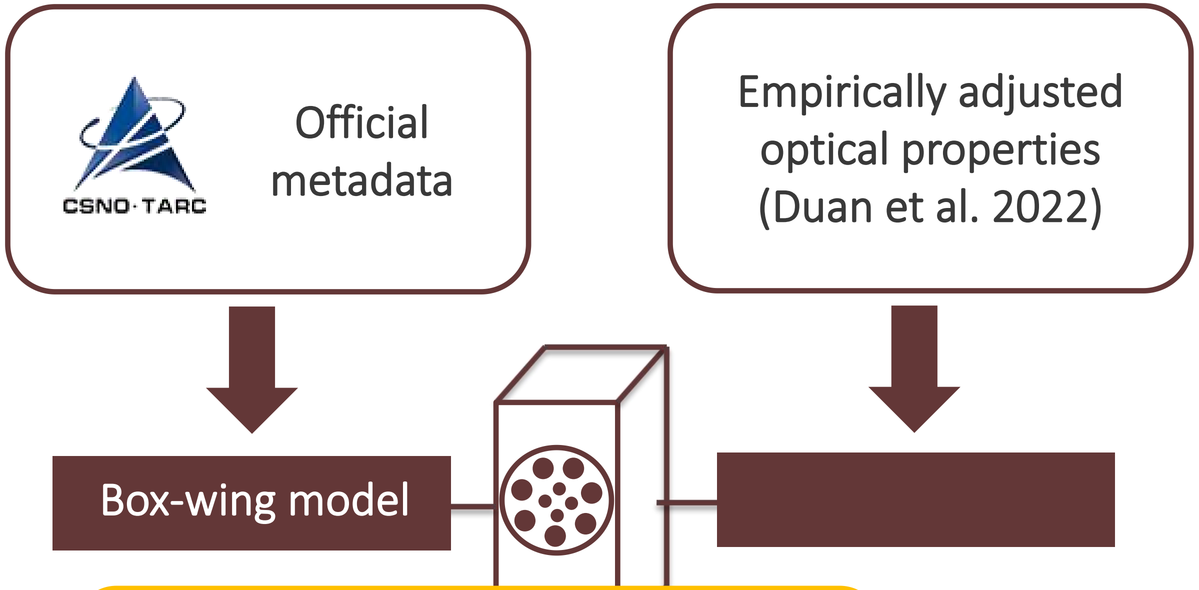
Empirically adjusted optical properties (Duan et al. 2022)

Box-wing model

$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + \cancel{D_{2C}\cos 2\Delta u + D_{2S}\sin 2\Delta u} \\ Y_0 \\ B_0 + B_{1C}\cos\Delta u + B_{1S}\sin\Delta u \end{bmatrix}$$

Solutions: SRP modeling





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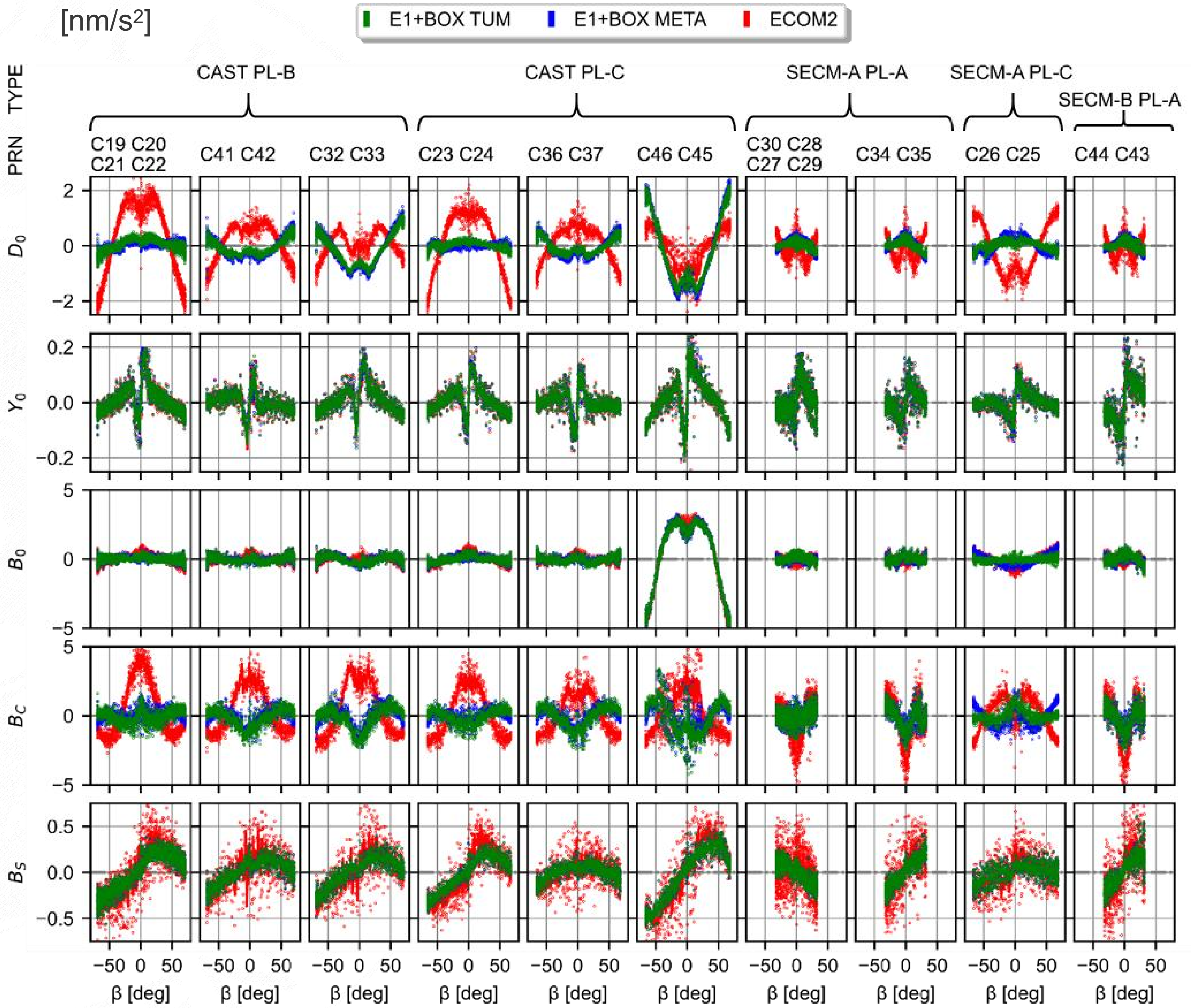
ECOM2 – Extended Empirical CODE Orbit Model (Arnold et al. 2015)

Solution name	ECOM parameters	Physical macro model
ECOM2	D_0, D_{2S}, D_{2C}, Y_0, B_0, B_{1C}, B_{1S} (7 parameters)	NO
E1+BOX TUM	D_0, Y_0, B_0, B_C, B_S (5 parameters)	Duan et al. (2022)
E1+BOX META		CSNO (2019)

ECOM parameters

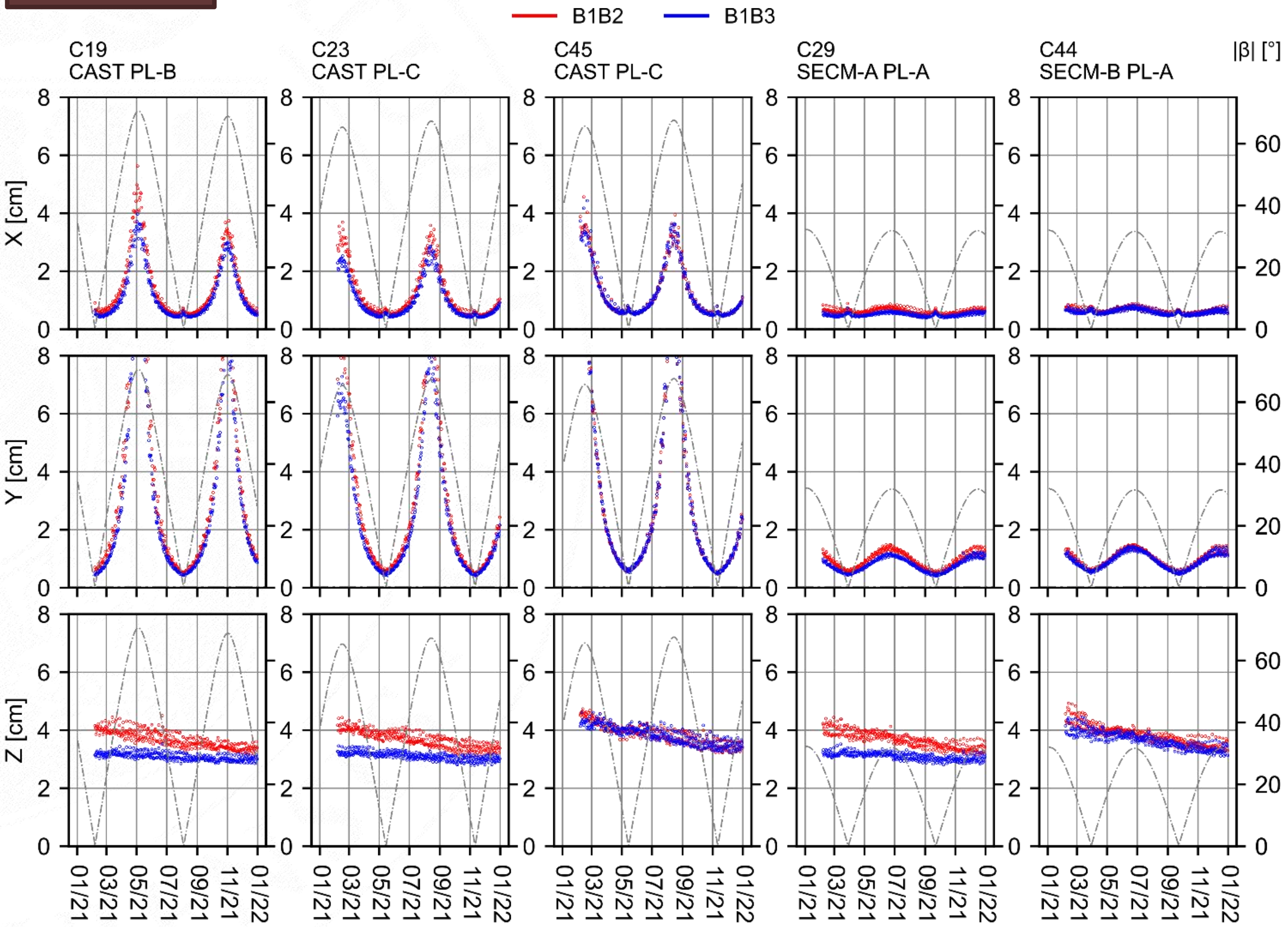


Offset removed

- Official metadata file specifies only one set of parameters for all the CAST satellites, and one set of parameters for the SECM-A/-B satellites.
- The analysis of the individual BDS-3 MEO satellites shows that we may distinguish up to ten different groups of satellites, which are placed on a given orbital plane and are characterized by similar patterns in the estimated ECOM parameters.
- Using an a priori box-wing model flattens the pattern visible in D_0, B_c; however, none of the two models diminish the estimated values completely to zero.

Formal errors - PCO

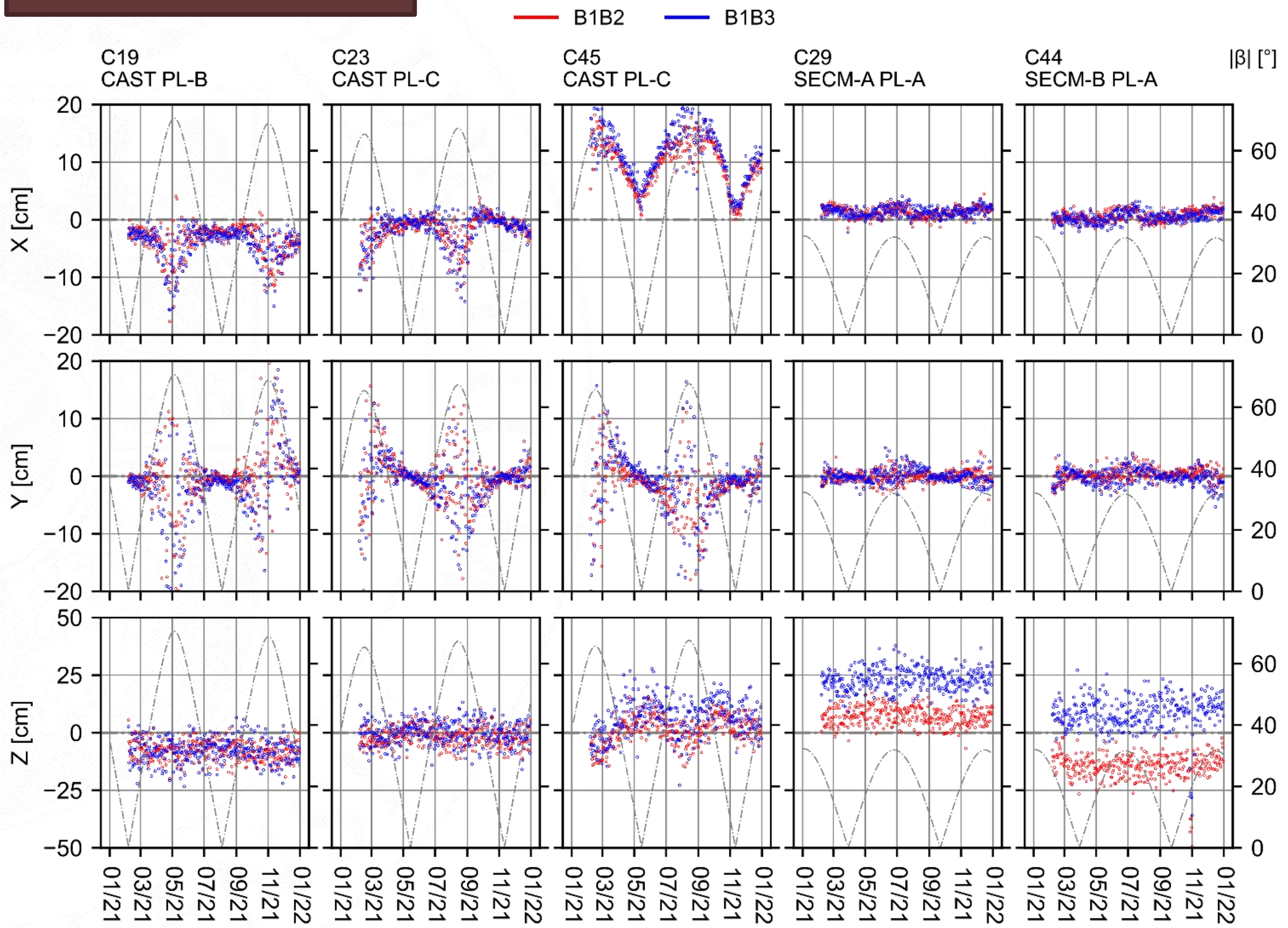
E1+BOX TUM



- No difference in the formal errors between the CAST and SECM satellites
- The estimation error for the PCO-x and PCO-y components is growing in parallel with the elevation of the sun above the orbital plane, especially for the PCO-y
- The secular decrease of the PCO-z formal error reflects the gradual increase in the number of tracking stations in the network, and amounts to roughly 5 mm
- The differences in the formal errors between the corresponding B1B2 and B1B3 test cases reach up to a few millimeters.

PCO estimates

Difference w.r.t. CSNO values



- Only periods corresponding to the |β| ≤ 45° provide stable horizontal PCO estimates whereas variations of up to ±20 cm appear for periods outside this range.
- The only exception is the group of the satellites C45/C46, for which all the estimated PCO components vary in time depending on the β angles.
- B1B3 and B1B2 solutions are consistent, except for the PCO-z corrections for BDS-3 SECM satellites

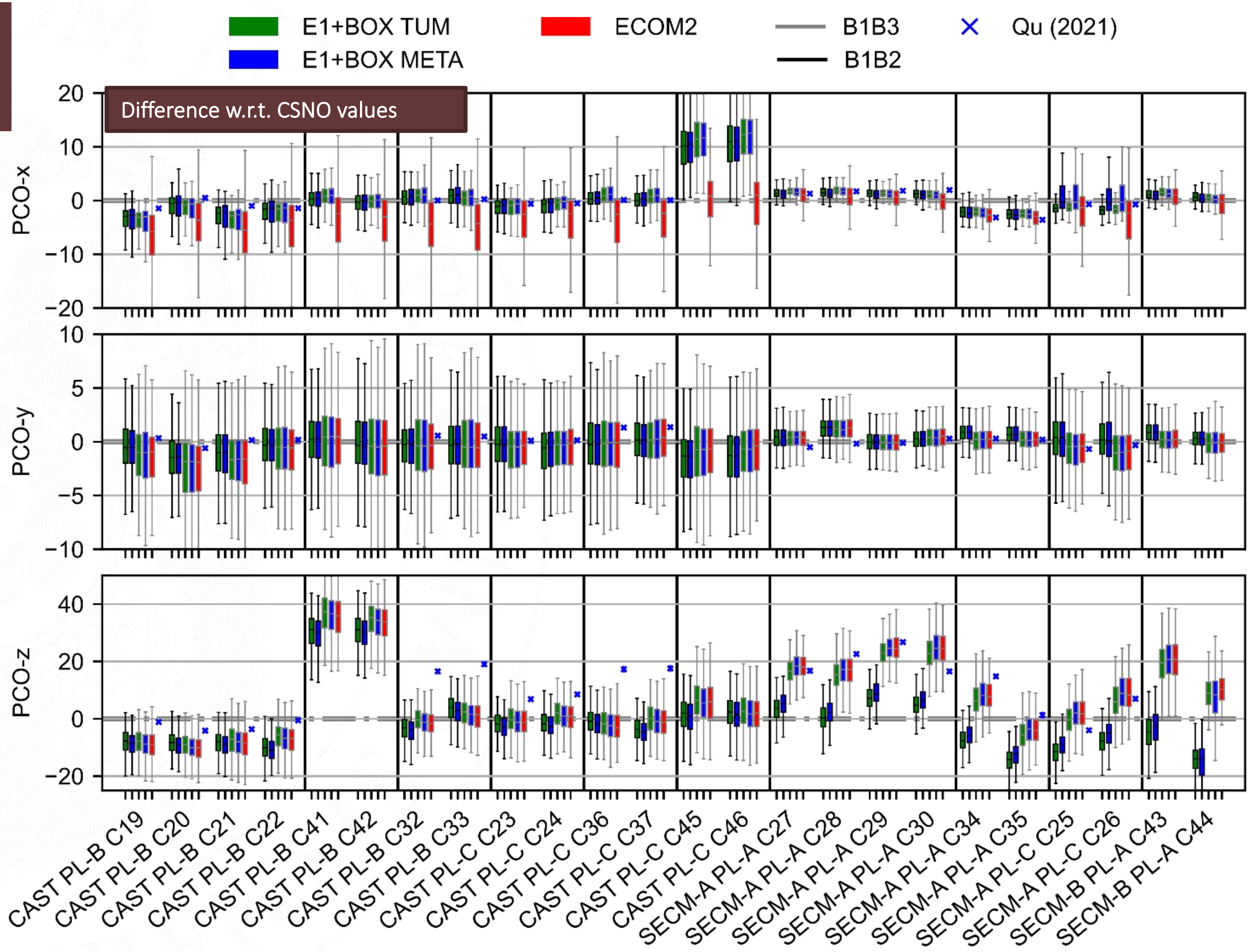
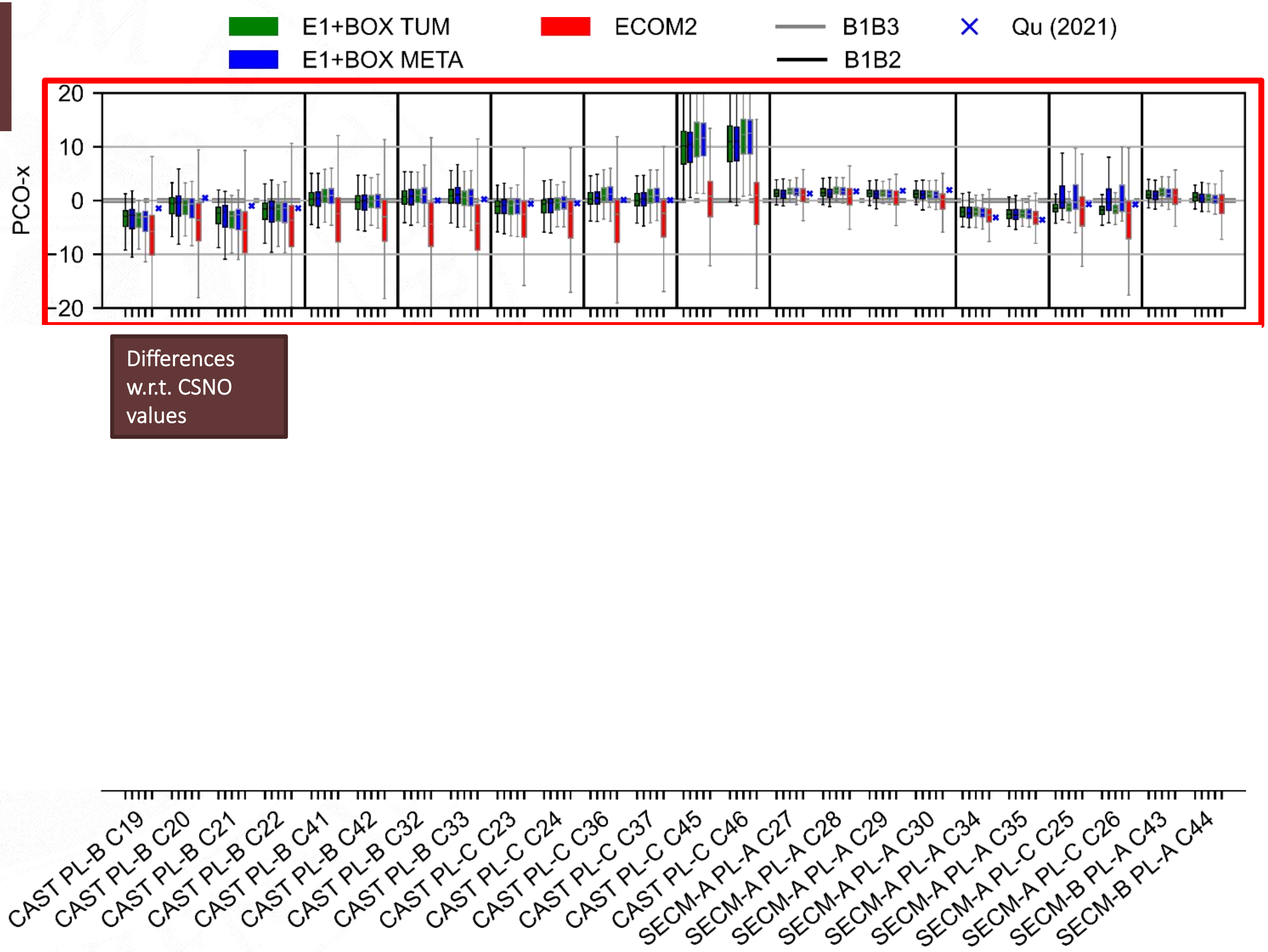


Figure presents the results of the PCO estimation in the form of box-whisker plots for all the satellites and all the considered solutions.

The satellites are subdivided into groups, consistetly with the analysis of the ECOM parameters.

Additionally, for comparison, we added next to our results the PCO values obtained by Qu et al. (2021) for the C19-C37 satellites.

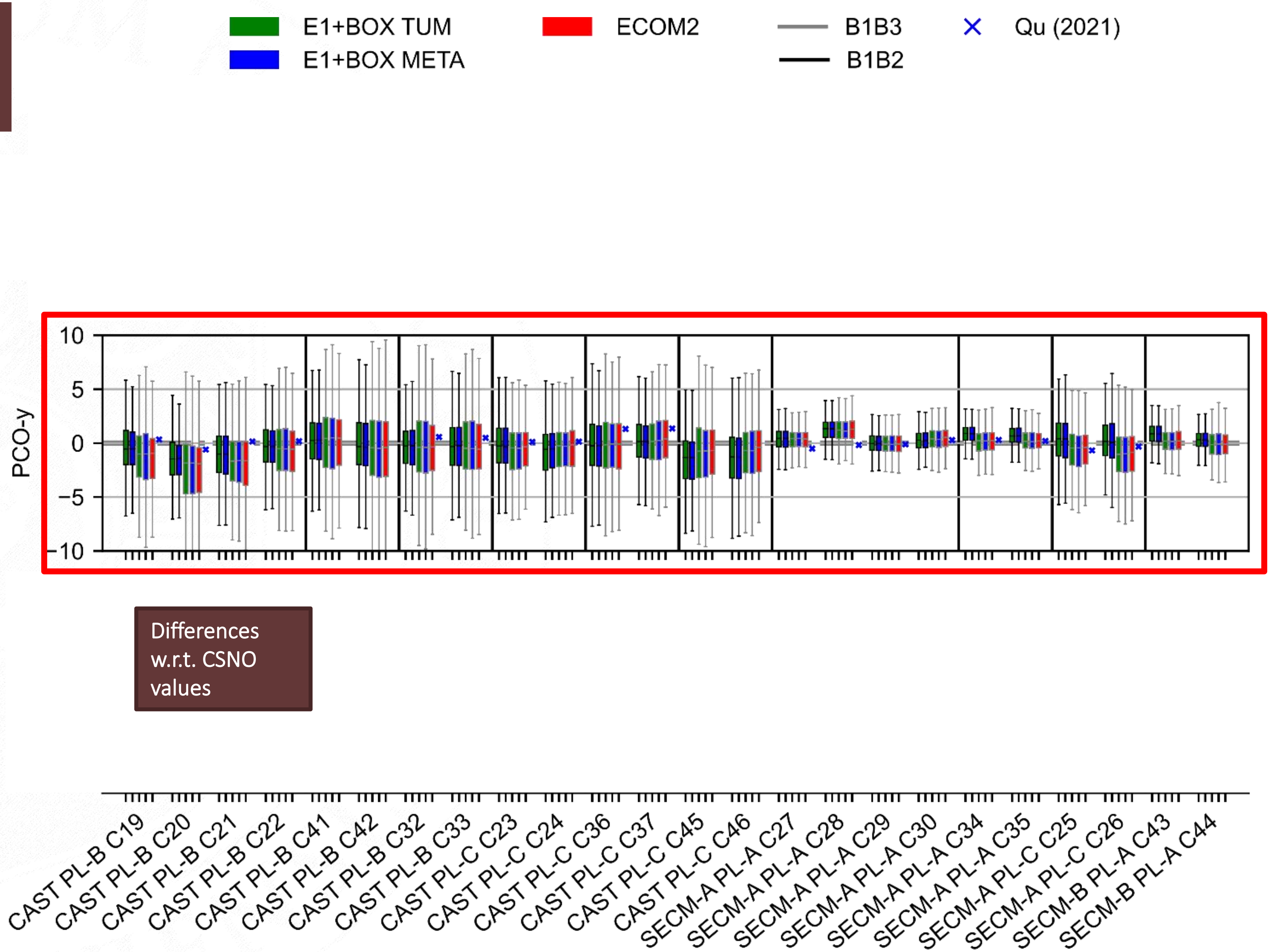
PCO-x



Differences w.r.t. CSNO values

- Agreement with the ground calibrations within 1 and 2 cm.
- This excludes the C45/C46 pair, for which an 8 cm offset is visible.
- Using ECOM2 is not suited for the determination of PCO-x, as visible in the spread of the estimated values.

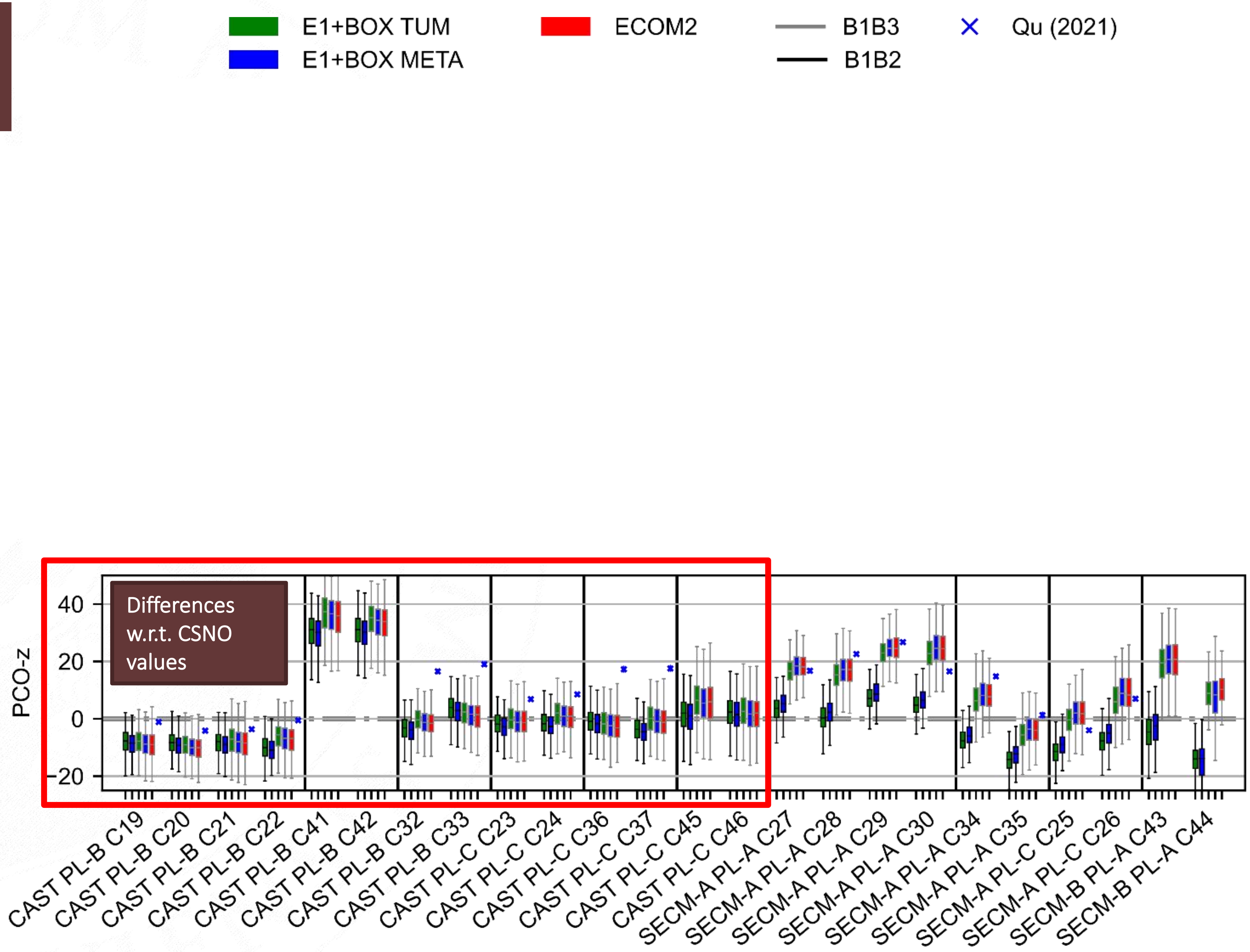
PCO-y



Differences w.r.t. CSNO values

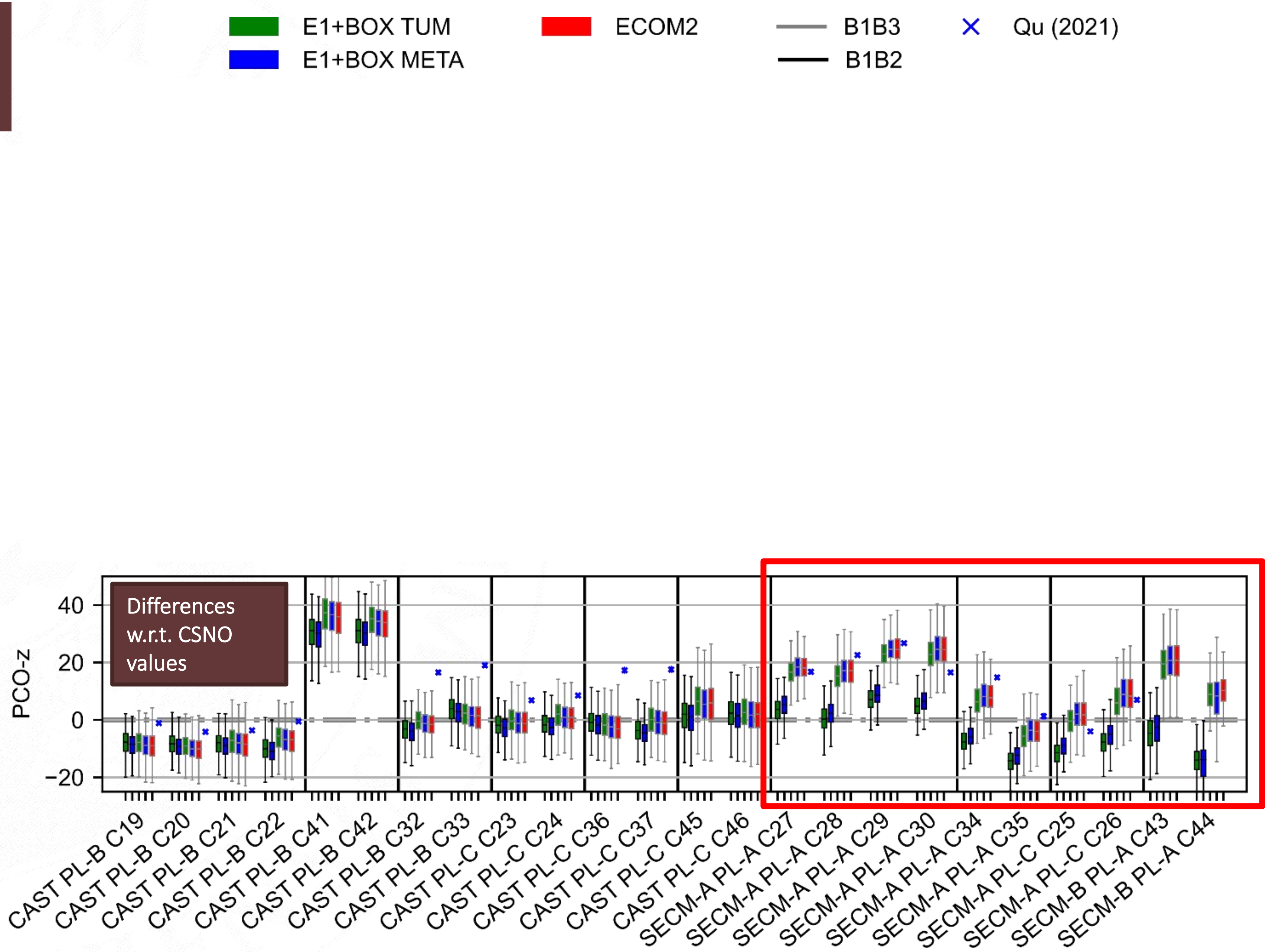
- The estimated values are on average consistent to the level of 1 cm with the ground calibrations, but with the standard deviation of estimates reaching 8 cm for the satellites on the orbital planes B and C, with wide β angle ranges.
- Different SRP solutions consistent between each other

PCO-z



- Standard deviation of the PCO corrections at the level of 5 cm
- Major clash between official calibrations and estimated PCOs for the pair of C41/C42 satellites reaching about 30-35 cm
- Orbital plane dependency in the mean offset observed in the PCO-z estimates for the CAST satellites. The **CAST satellites orbiting plane B** have a bias in the estimated values at the level of **-10 to -8 cm**, while the bias for the CAST satellites on **the plane C is close to zero**.
- Difference between B1B2 and B1B3 is very similar for all the CAST satellites

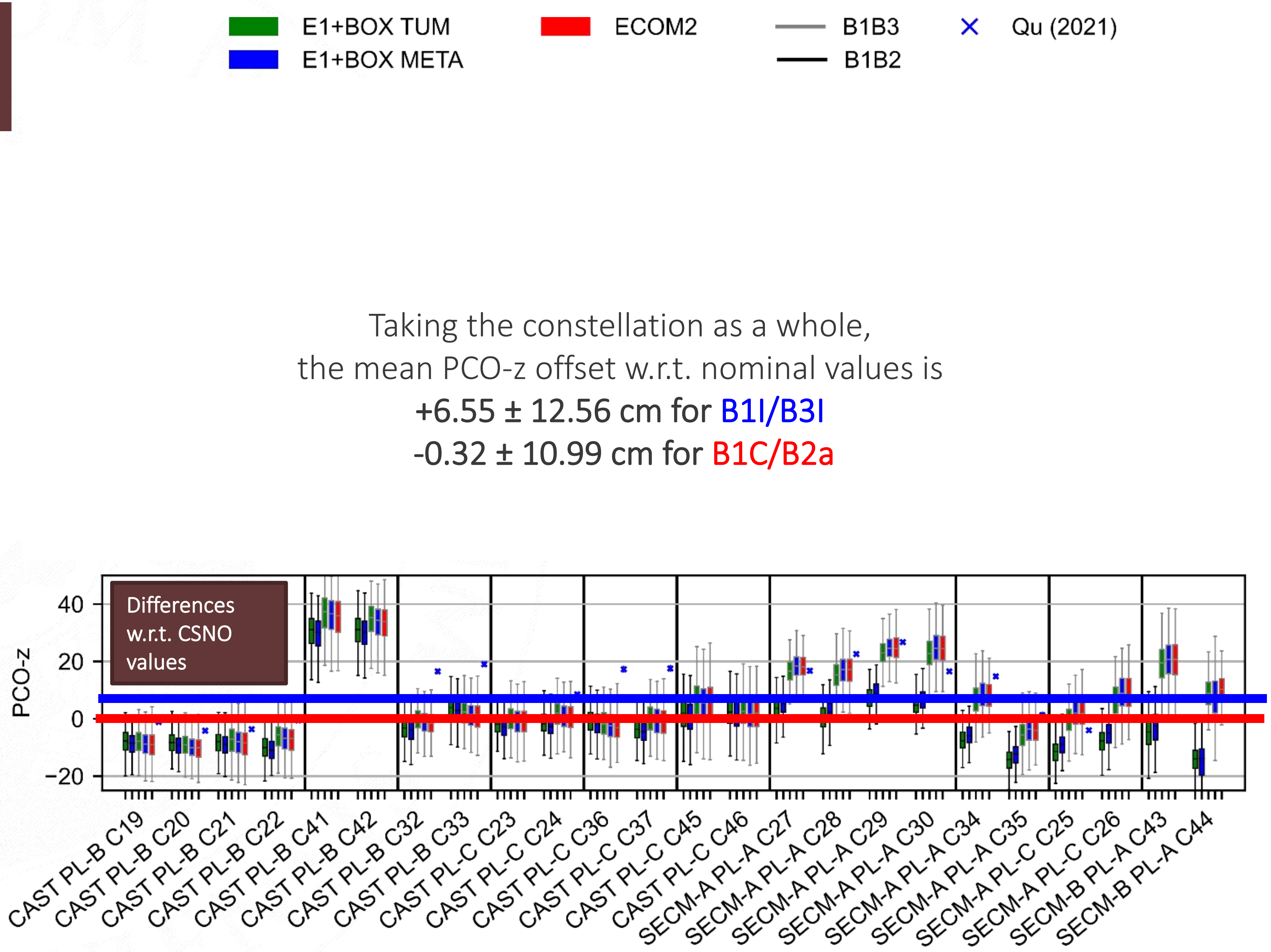
PCO-z



- Substantial scatter for individual satellites with no orbital-plane or satellite subtype dependence.
- Difference of 10-20 cm between B1I/B3I and B1C/B2a estimates
- In contrast to the ground calibrated nominal values, the observed SECM PCO-z exposes an obvious frequency dependence. We might speculate that the SECM satellites suffer from large near-field effects causing systematic differences between factory calibrations of the standalone antenna array and the antenna array as integrated with the satellite.

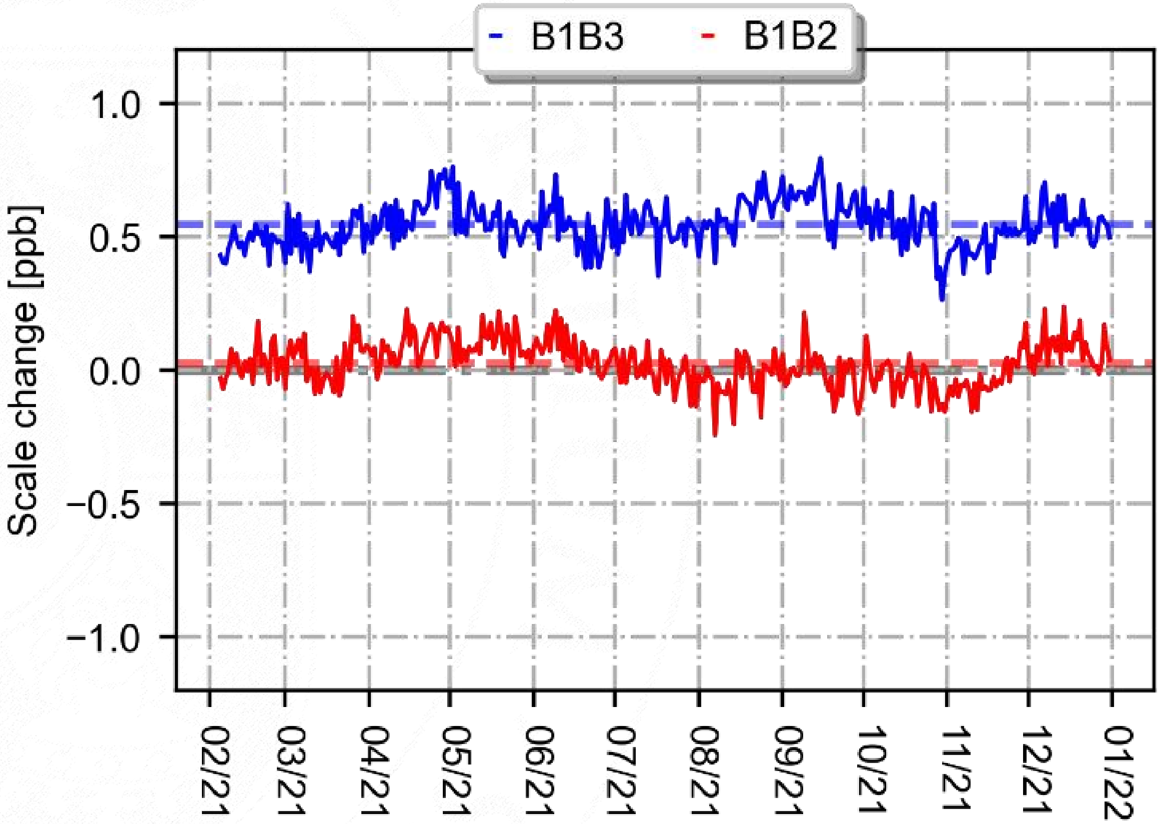
PCO-z

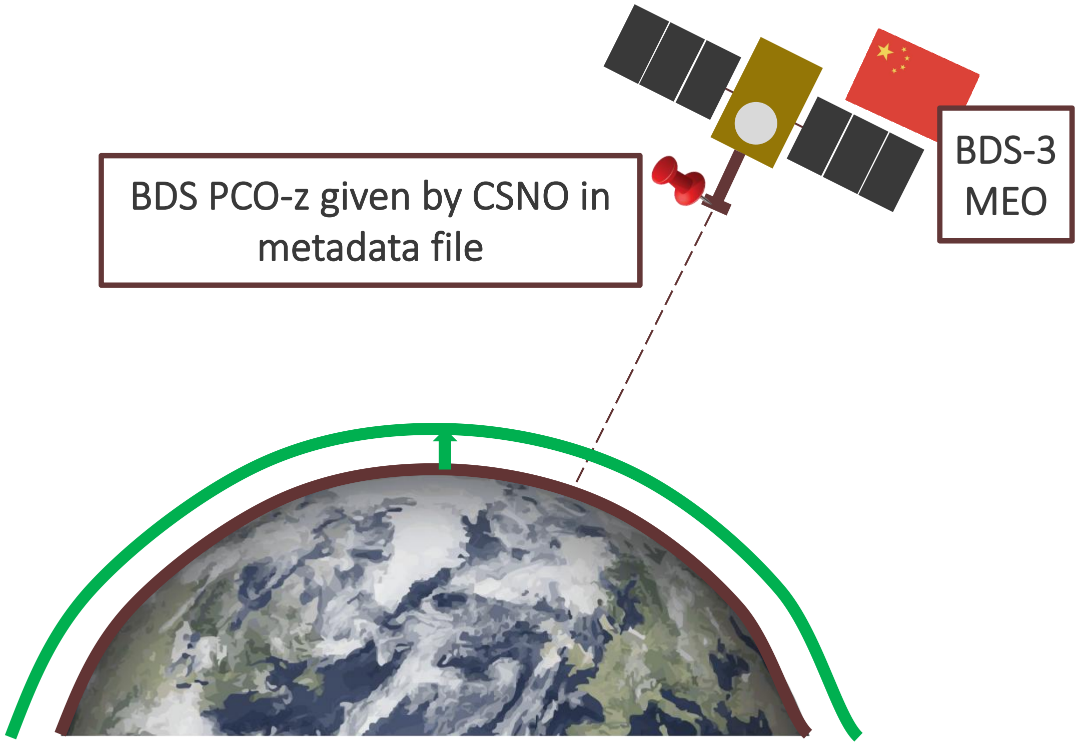
Taking the constellation as a whole,
the mean PCO-z offset w.r.t. nominal values is
+6.55 ± 12.56 cm for B1I/B3I
-0.32 ± 10.99 cm for B1C/B2a



Differences w.r.t. CSNO values

Scale





BDS PCO-z given by CSNO in metadata file

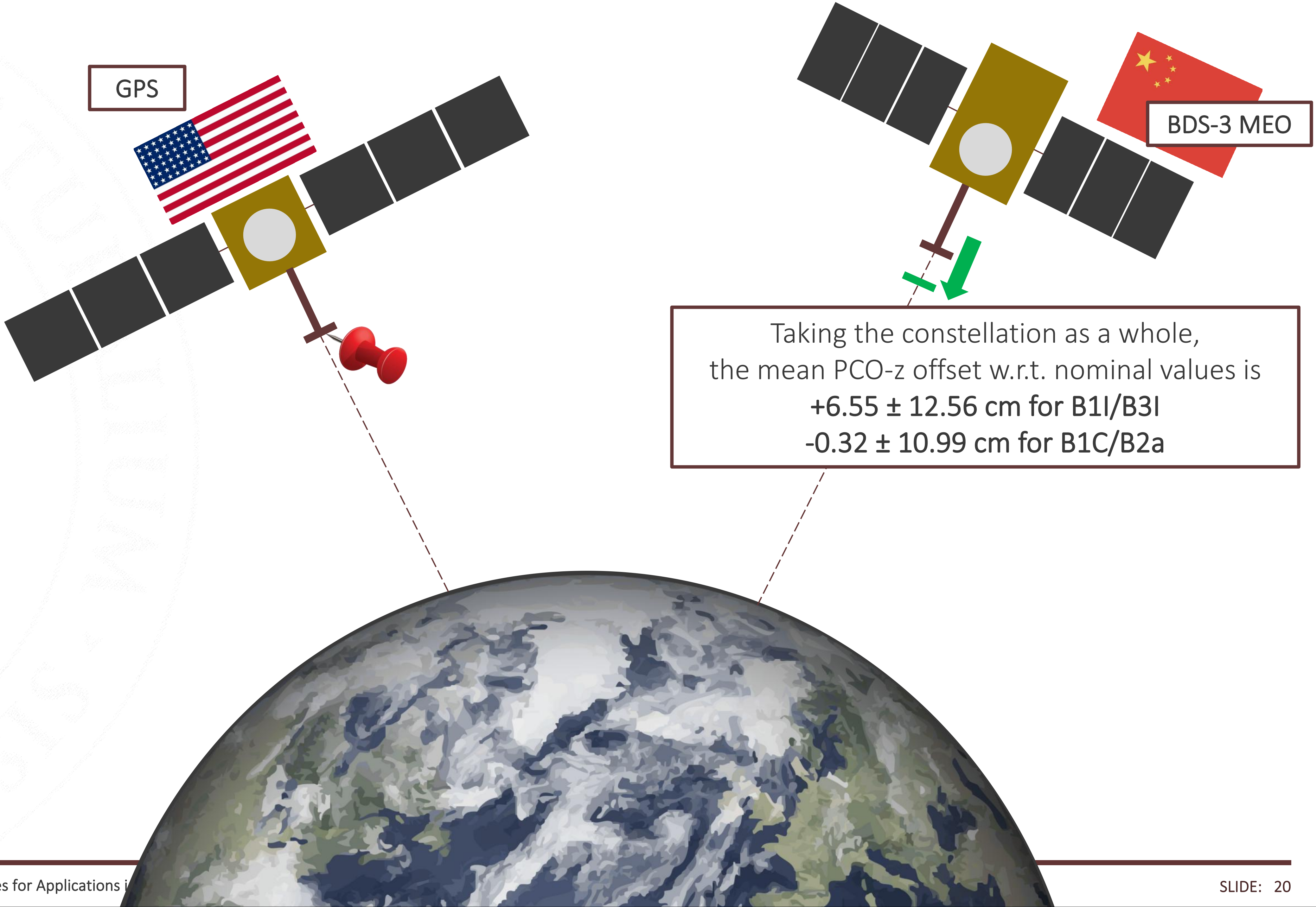
BDS-3 MEO

- The mean scale bias equals
  +0.546 ± 0.085 ppb for B1I/B3I
  +0.026 ± 0.085 ppb for B1C/B2a

- The scale discrepancy between the B1B3 and B1B2 solutions arises to a great extent from the uncertain quality of the SECM PCO calibrations, which certainly do not reflect the frequency dependence of the PCOs.

Conclusions

Analysis 1



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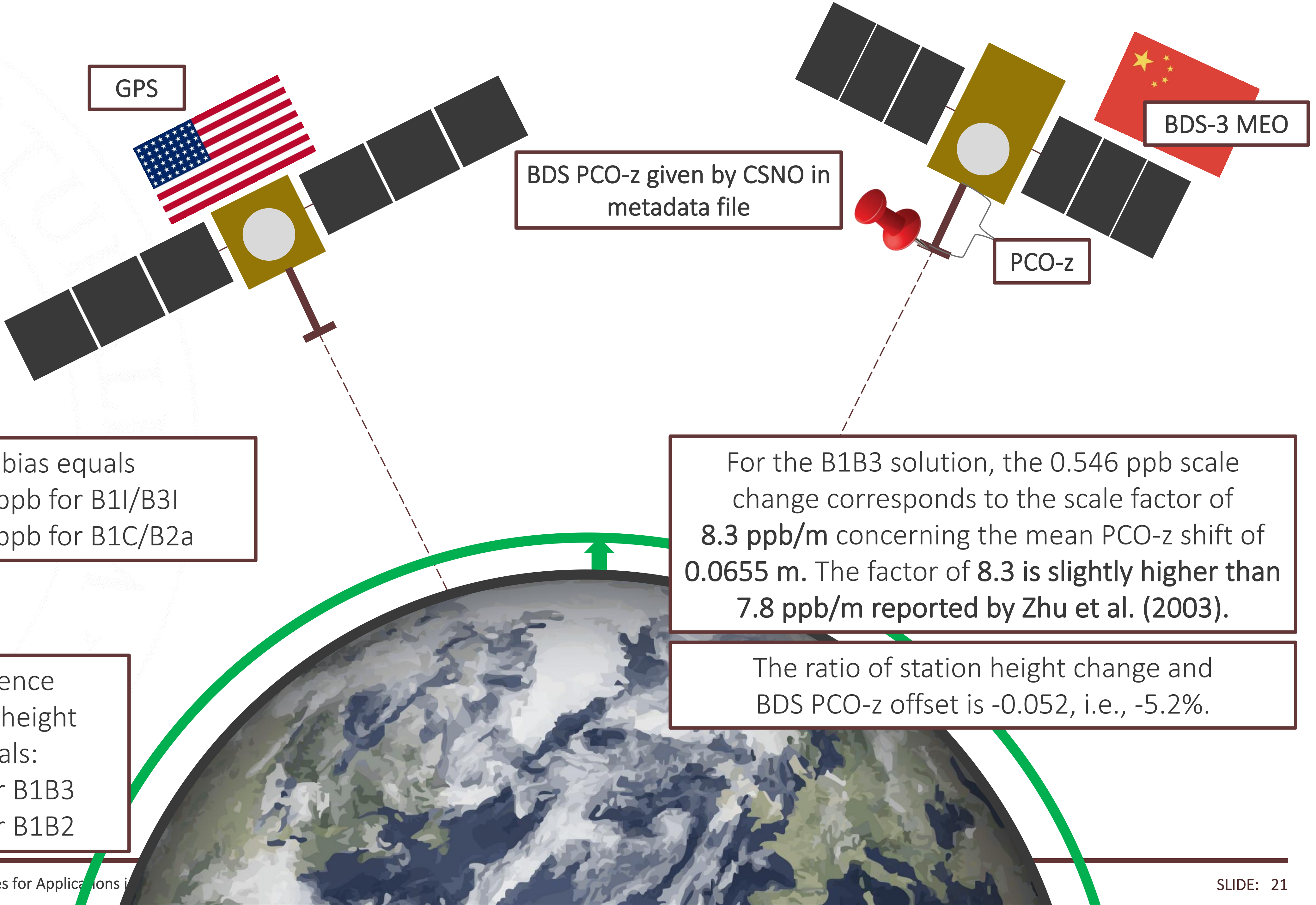
Conclusions

Analysis 2



- The mean scale bias equals
  +0.546 ± 0.085 ppb for B1I/B3I
  +0.026 ± 0.085 ppb for B1C/B2a

- The mean difference observed in the height component equals:
  3.4 ± 0.6 mm for B1B3
  0.2 ± 0.4 mm for B1B2

For the B1B3 solution, the 0.546 ppb scale change corresponds to the scale factor of **8.3 ppb/m** concerning the mean PCO-z shift of **0.0655 m.** The factor of **8.3 is slightly higher than 7.8 ppb/m reported by Zhu et al. (2003).**

The ratio of station height change and BDS PCO-z offset is -0.052, i.e., -5.2%.

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FOR MORE INFORMATION:

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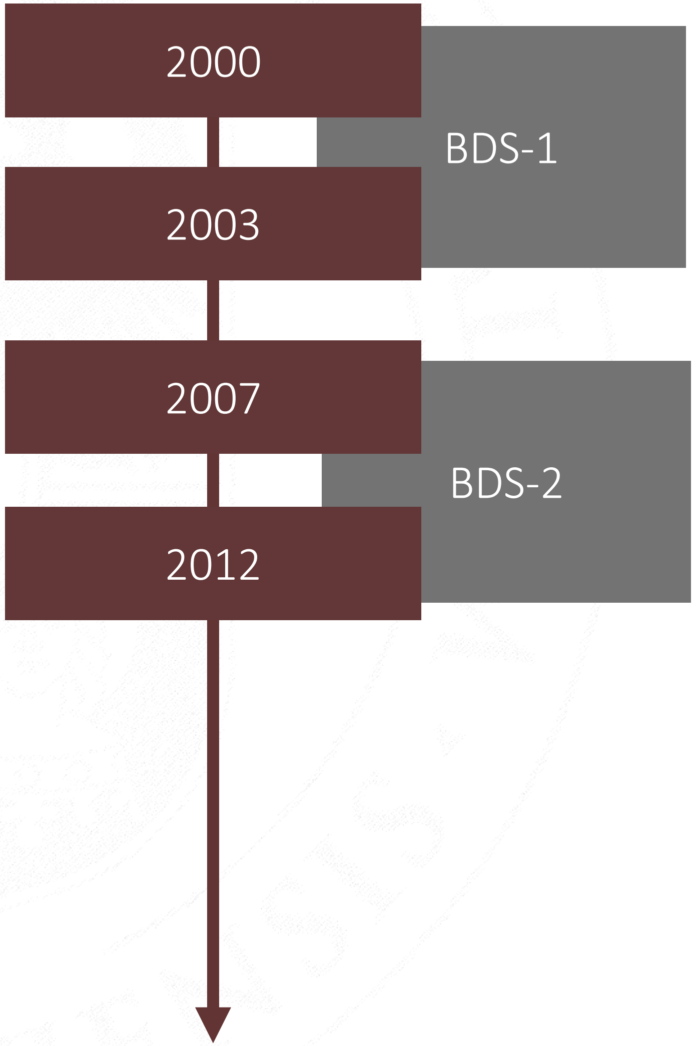
BACKUPS

BeiDou Constellation



2000	BDS-1	the first pair of BeiDou satellites was deployed
2003		the BeiDou first demonstration subsystem (BDS-1) with three GEostationary Orbit (GEO) satellites
2007	BDS-2	The launch of the first Medium Earth Orbit (MEO) satellite started the second stage of the regional radio navigation satellite service (BDS-2) for the Asia-Pacific region.
2012		BDS-2 became complete in 2012 with 5 GEO, 4 MEO, and 5 Inclined GeoSynchronous Orbit (IGSO) satellites.

BeiDou Constellation

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2012		BDS-2 became complete in 2012 with 5 GEO, 4 MEO, and 5 Inclined GeoSynchronous Orbit (IGSO) satellites.
2015	BDS-3	The built of the global coverage alternative to GPS, GLONASS and Galileo began with the launch of the in-orbit validation BDS-3 experimental (BDS-3s) constellation consisting of 2 IGSO and 3 MEO satellites.

BeiDou Constellation

2000

BDS-1

2003

2007

BDS-2

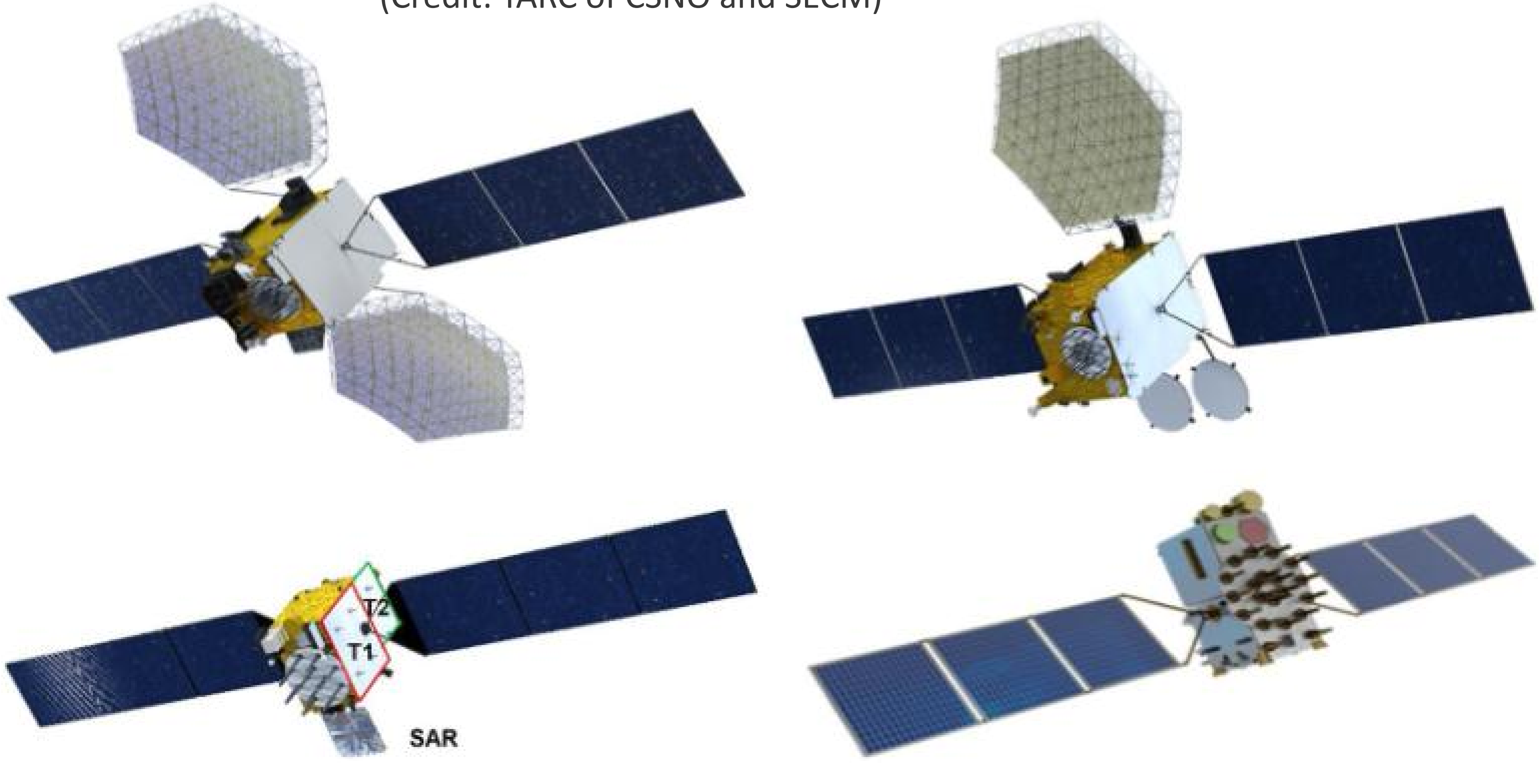
2012

2015

BDS-3

2020

Images of BDS-3 GEO, IGSO, CAST MEO, and SECM MEO satellites. (Credit: TARC of CSNO and SECM)



Success of the in-orbit validation phase sparked the deployment of the proper BDS-3 constellation, which became complete and operational in 2020 with 30 satellites in total, including **3 GEO, 3 IGSO, and 24 MEO.**

Experiment setup

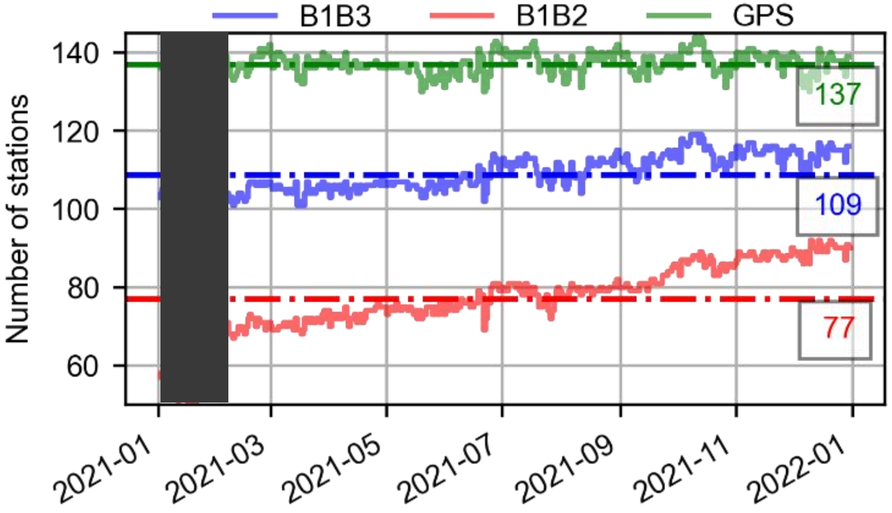
Two main issues remain nowadays in tracking BDS-3 satellites.

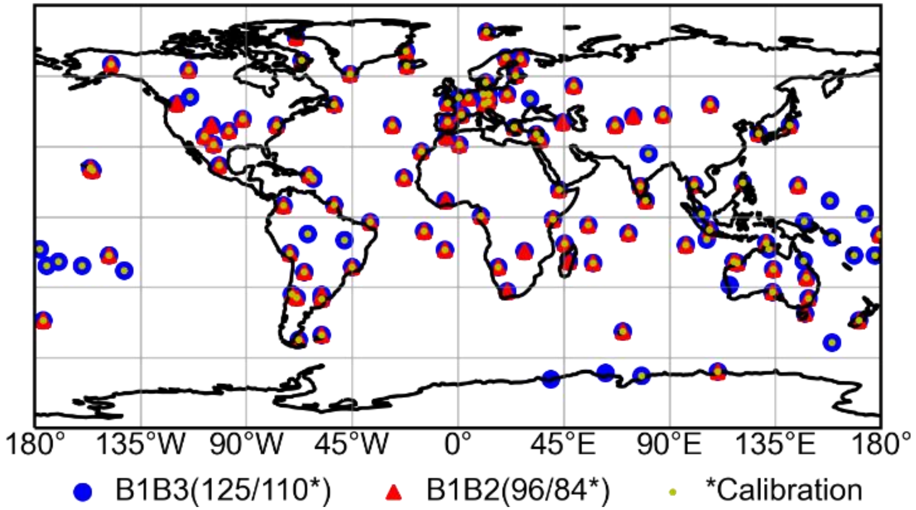
- Not all deployed BDS-3 satellites can be tracked by an equal number of receivers, mainly due to the limitation of tracking channels or outdated firmware.
- Despite a wide range of frequencies and signals transmitted by BDS satellites, not all of them are supported by the receivers.

Network of 145 stations, all of which track GPS satellites.
In 2021, the network includes on average **109 and 77 stations tracking BDS-3 B1I/B3I and B1C/B2a signal pairs, respectively.**

At least 88 % of the selected stations tracking BDS-3 make use of antennas with the multi-GNSS calibration provided by Geo++.

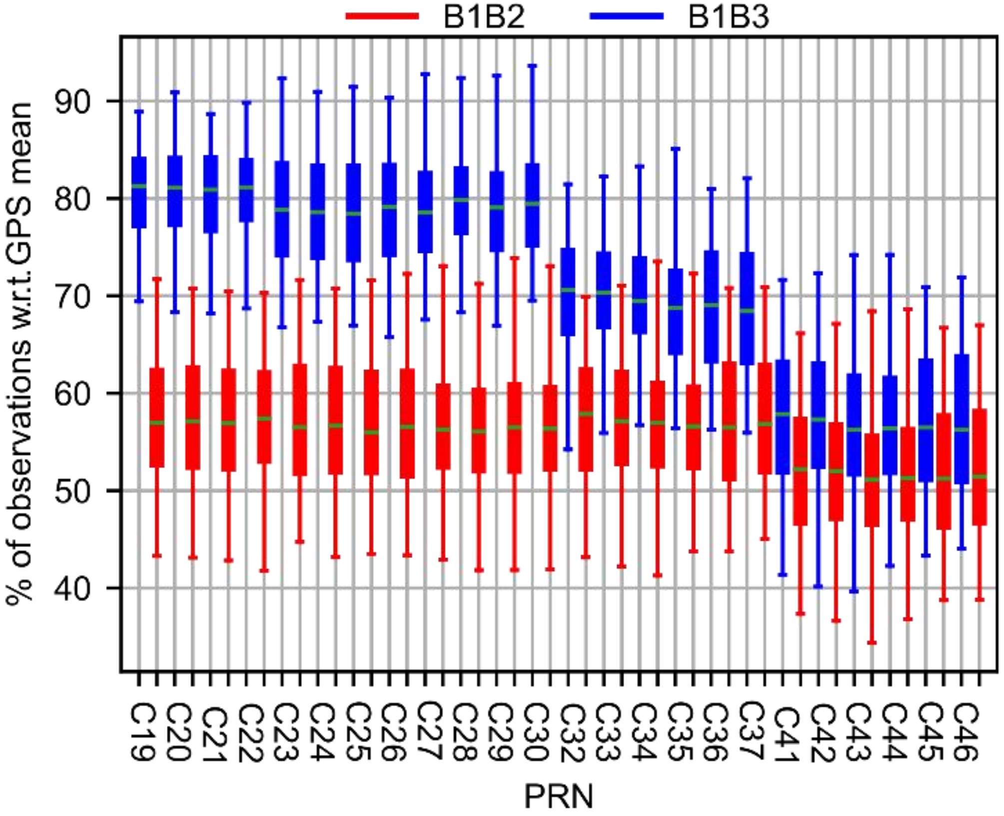
Until the 6th of February 2021 the number of stations supporting B1C/B2a tracking in the network was too poor to deliver solutions of the comparable quality to the rest of the year.





Different numer of observations

The percentage of observations available for the individual BDS-3 satellites compared to the average number of observations per GPS satellite in the analysis period.



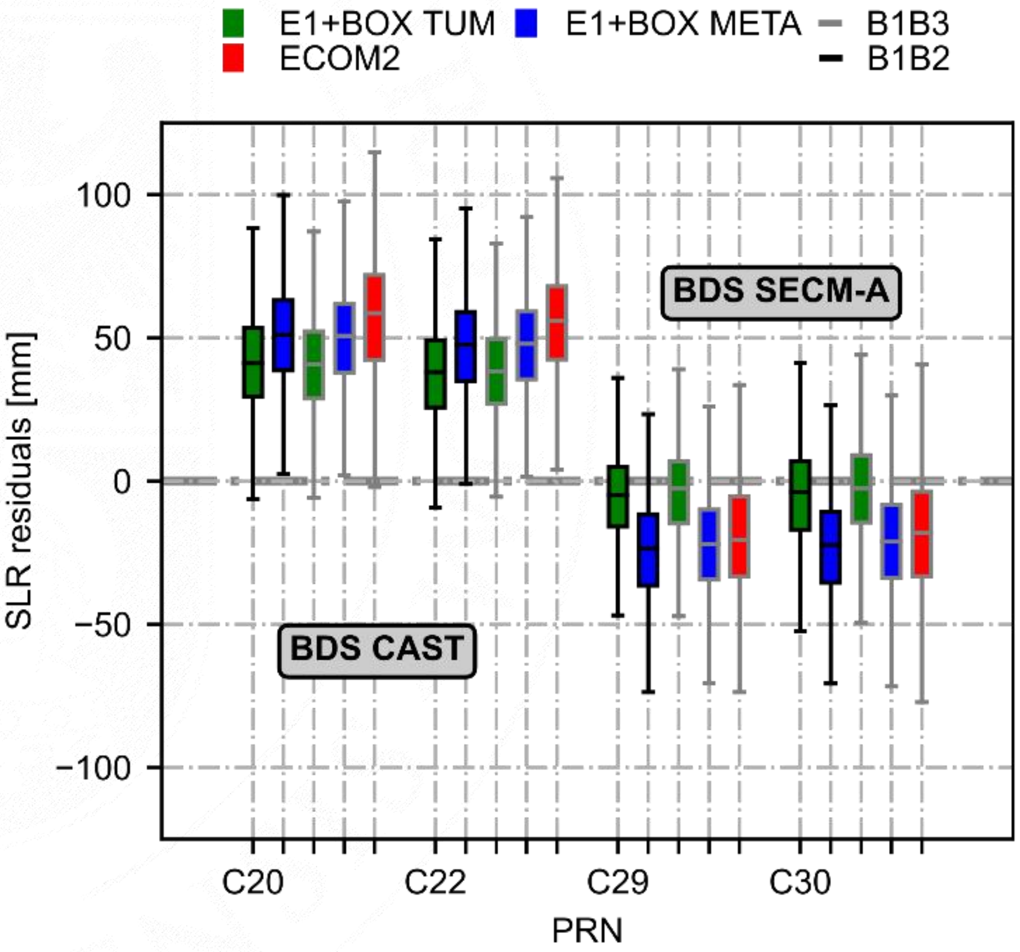
the mean number of observations w.r.t. GPS

80% (PRNs up to C30); 70% (PRNs C32-C37); 58% (PRNs> C41).

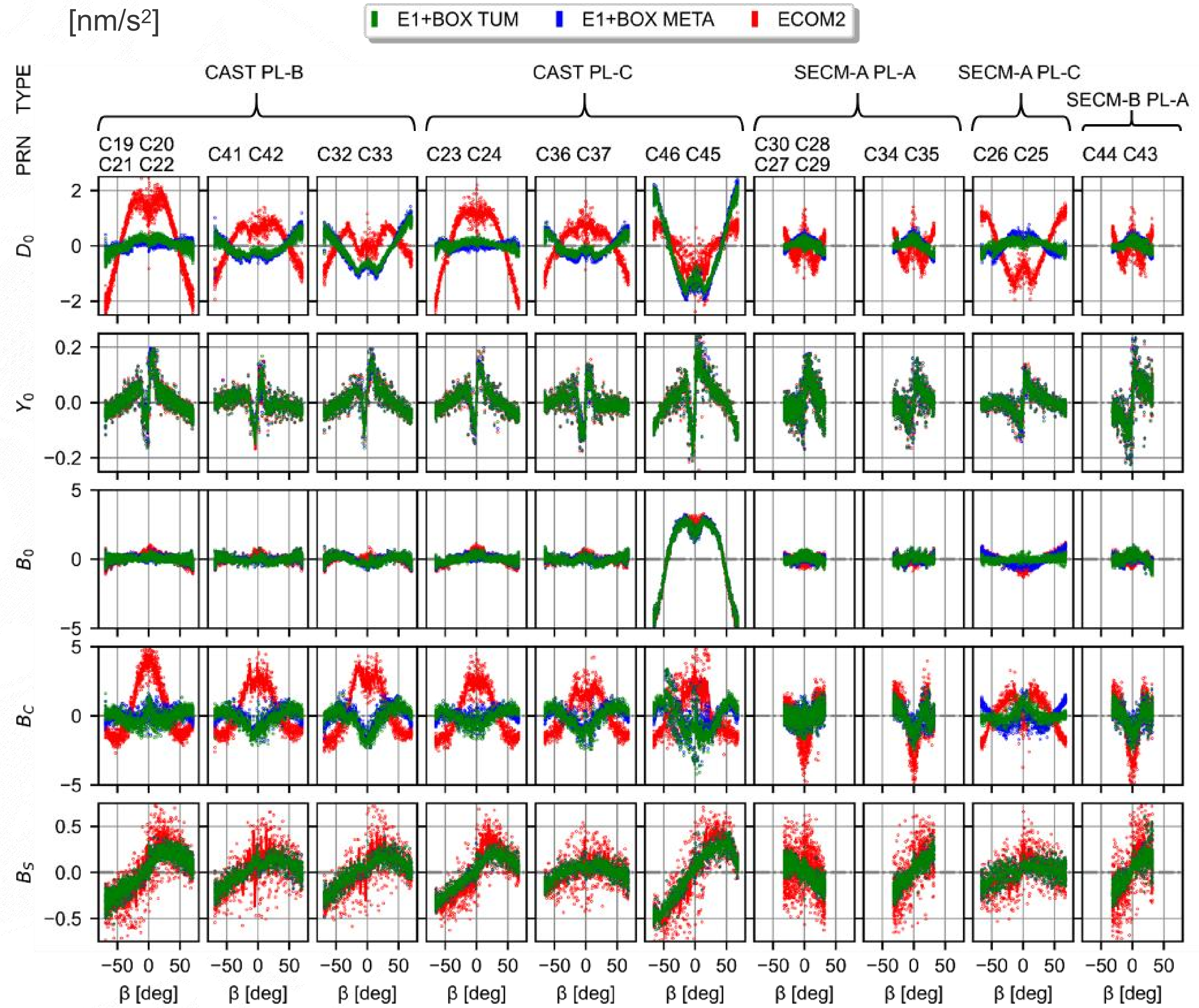
58% (PRNs up to C37) and 52% (PRNs>C37)

- Javad TRE_3, Leica GR50, Septentrio AsteRx4 and PolaRx5, and Trimble Alloy → B1I/B1C/B2a/B3I signals
- Some of the PolaRx5 receivers in the network do not provide observations from PRNs greater than C41
- Trimble NetR9 receivers track only BDS-3 B1I/B3I signals from the satellite channels up to C32
- The B1C/B2a signals are not tracked also by individual Trimble Alloys, and Septentrio PolaRx5s in the network

Orbit validation using Satellite Laser Ranging



- Only 2 BDS-3 SECM-A (C29 and C30) and 2 BDS-3 CAST (C20 and C22) tracked by the International Laser Ranging Service
- Minor differences between the corresponding B1B3 and B1B2 solutions (in favor of B1B3)
- Using the E1+BOX TUM solution model results in the smallest offset and standard deviation of SLR residuals for both BDS CAST and SECM-A **satellites (standard deviation of SLR residuals at the level of 24-28 mm).**



Orbit validation ECOM parameters

- The a priori box-wing model should, ideally, account for all non-gravitational perturbing forces acting on a satellite.
- In both E1+BOX solutions, the ECOM coefficients are estimated on top of an a priori box-wing model. Therefore, any deviations from zero in the estimated ECOM parameters reflect the box-wing model deficiencies.