

BDS phase center corrections: initial results and validation

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Ground and in-orbit calibrations of BDS PCO/PCV

● Ground calibrations

- Satellite and frequency-specific (B1/B2/B3) PCOs for BDS-2 as well as BDS-3 released by China Satellite Navigation Office (CSNO)
- <http://en.beidou.gov.cn/SYSTEMS/Officialdocument/2019a12/P020200323536112807882.atx>

● In-orbit estimations

Reference	BDS-2	BDS-3	PCO	PCV	Frequency	Frame
Dilssner et al. (2014)	√		√	√	B1I/B2I	IGS08
Guo et al. (2016)	√		√	√	B1I/B2I	IGS08
Huang et al. (2018)	√		√		B1I/B2I	IGS08
Yan et al. (2019)		√ (Up to C35)	√	√	B1I/B3I	IGS14
Xia et al. (2020)	√	√ (Up to C37)	√		B1I/B3I	IGS14
Qu et al. (2021)	√	√ (Up to C37)	√	√	B1I/B3I	IGS14,R3
Villiger et al. (2021)	√	√	√	√	B1I/B3I	R3
Zajdel et al. (2022)	√	√ (no IGSO)	√		B1I/B3I, B1c/B2a	IGS14

IGS recommended values

- IGS14_WWWW.atx
 - BDS-2: IGS conventional block-specific PCO values, and zero PCV
 - BDS-3: Frequency and block-specific PCOs from TARC/CSNO since week 2056, and zero PCV
- IGS20_WWWW.atx
 - BDS-2: AC- and block means of PCO estimation from Dilssner et al. (2014), Guo et al. (2016), Siphthorpe et al. (2016), and Huang et al. (2018) for B1I/B2I, synthetic values derived for B3I to keep consistency with IF of B1/B2I; no PCV
 - BDS-3s: values from manufacturer or control center; no PCV
 - BDS-3: CSNO ground calibrations; no PCV

Issues and previous findings

- PCV

- 9° and 13° maximum nadir for IGSO and MEO, no extension
- The estimations are not adopted by IGS, possibly due to IF combination

- PCO

- Suspicious quality of ground calibration values of C41 and C42 from CAST as well as those from SECM (Zajdel et al., 2022)
- Potential scale inconsistency between BDS disclosed PCO and IGS20 or BDS-2 and BDS-3 in igs20.atx

- Terrestrial reference frame scale (Zajdel et al., 2022)

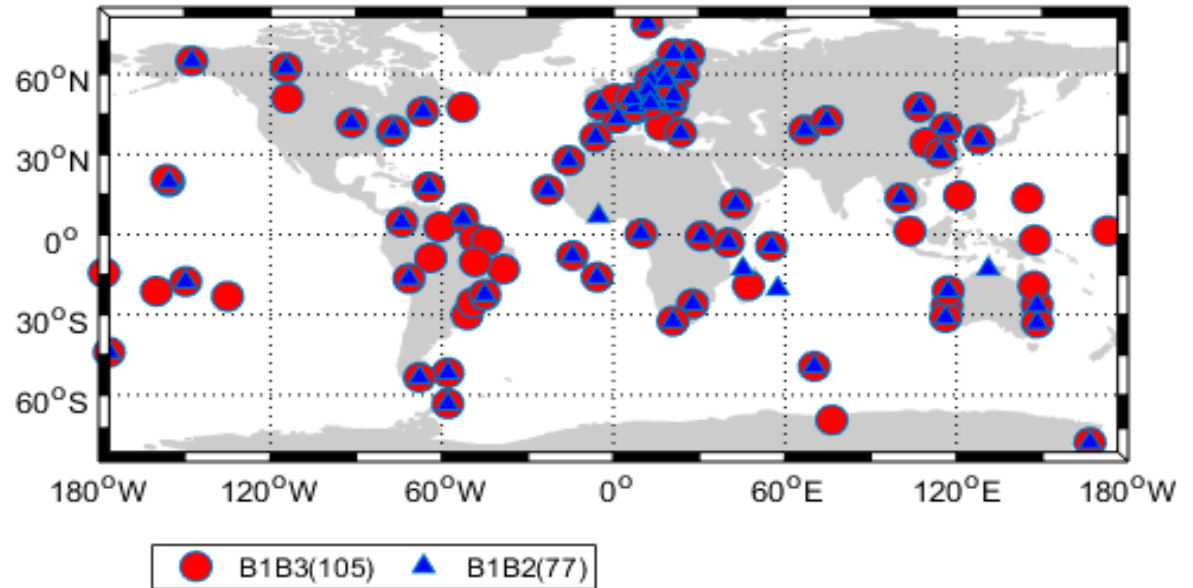
- The scale discrepancy between the B1I/B3I and B1c/B2a solutions
- The mean scale bias of 0.546 ppb is seemingly close to the scale difference between ITRF2020 vs. ITRF2014 (0.42 ppb)

Methodology

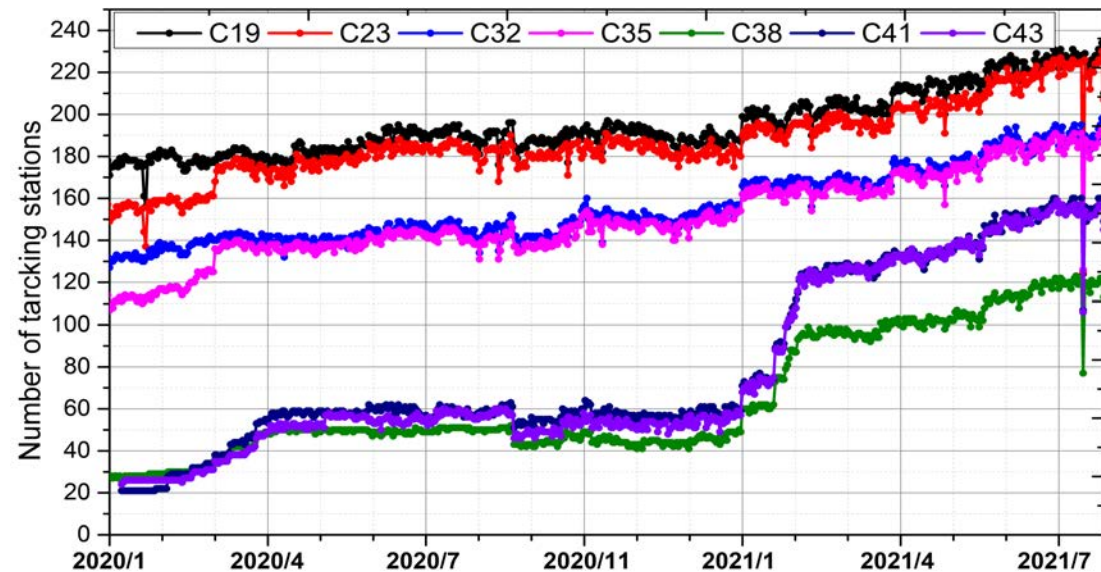
- PCV estimation
 - IGS ground as well as FY3D onboard tracking data
 - FY3D: BDS-2 only in B1I and B2I during DOY 45-210, 2017
 - IF combination as well as raw data
- PCO estimation
 - IGS ground or their combination of ISL measurements in IGS14
 - One year (2021) IGS ground data
 - ISL measurements during DOY 10-238, 2020
 - BDS only processed only with NNT constrain
- Terrestrial reference frame scale
 - Selections of satellite group

Status of tracking stations

- Distribution of ground stations
 - 105 stations used for B1I/B3I
 - 77 stations used for B1c/B2a

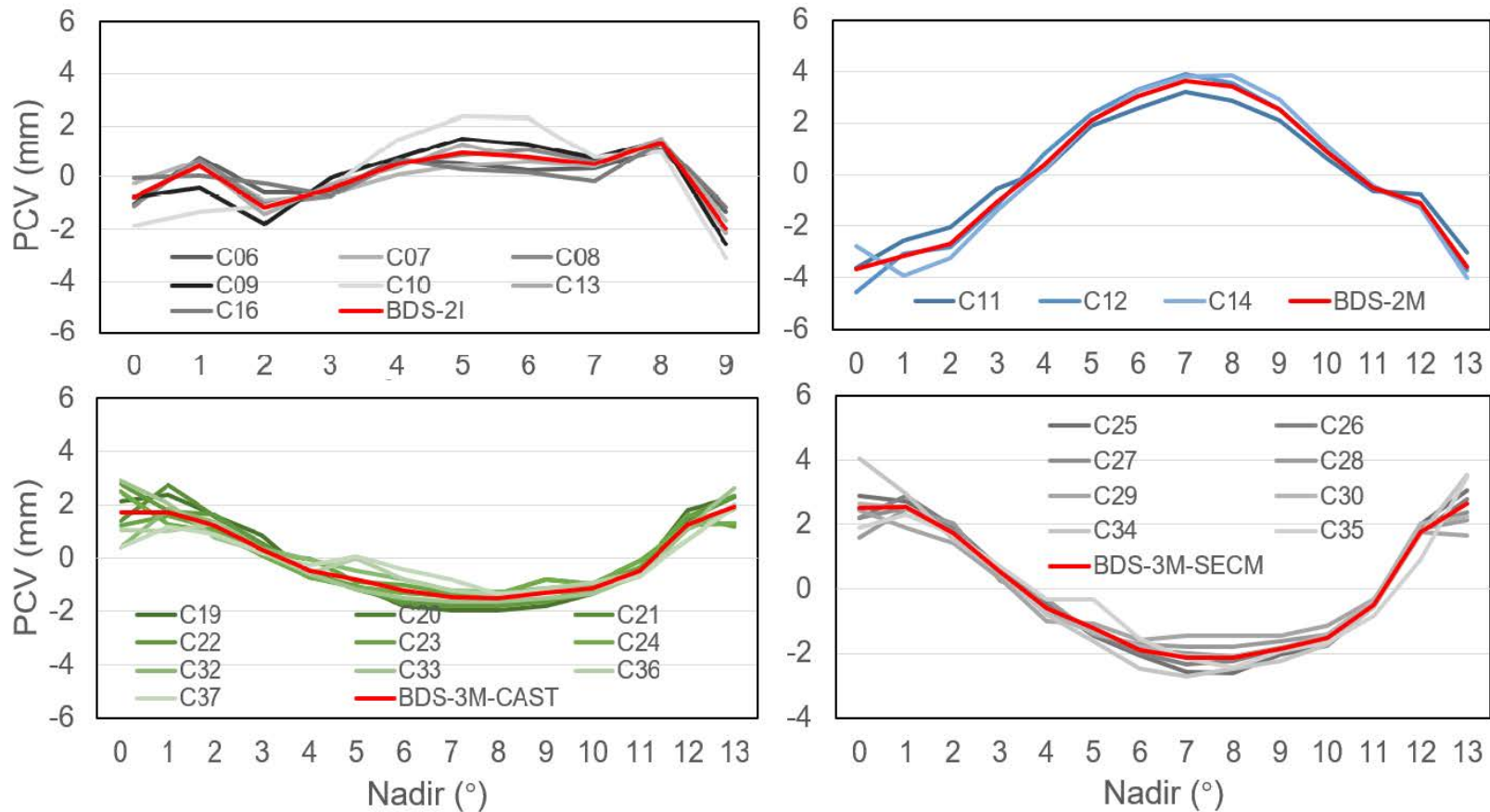


- Daily number of stations for BDS tracking



BDS phase center variation

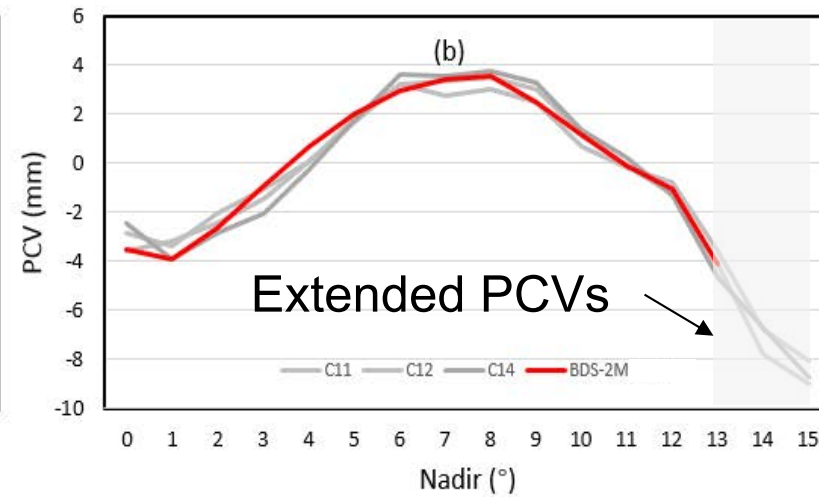
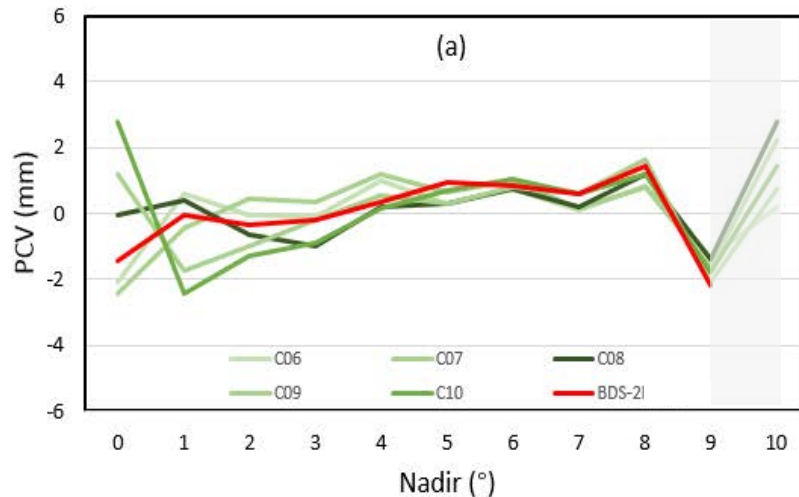
- Block-specific and nadir-dependent PCV values for B1I and B3I IF combination based on ground stations



Extension of BDS phase center variations

- BDS-2: FY3C with B1I and B2I tracking capability

- Extension to 10° and 15° for IGSO and MEO satellites

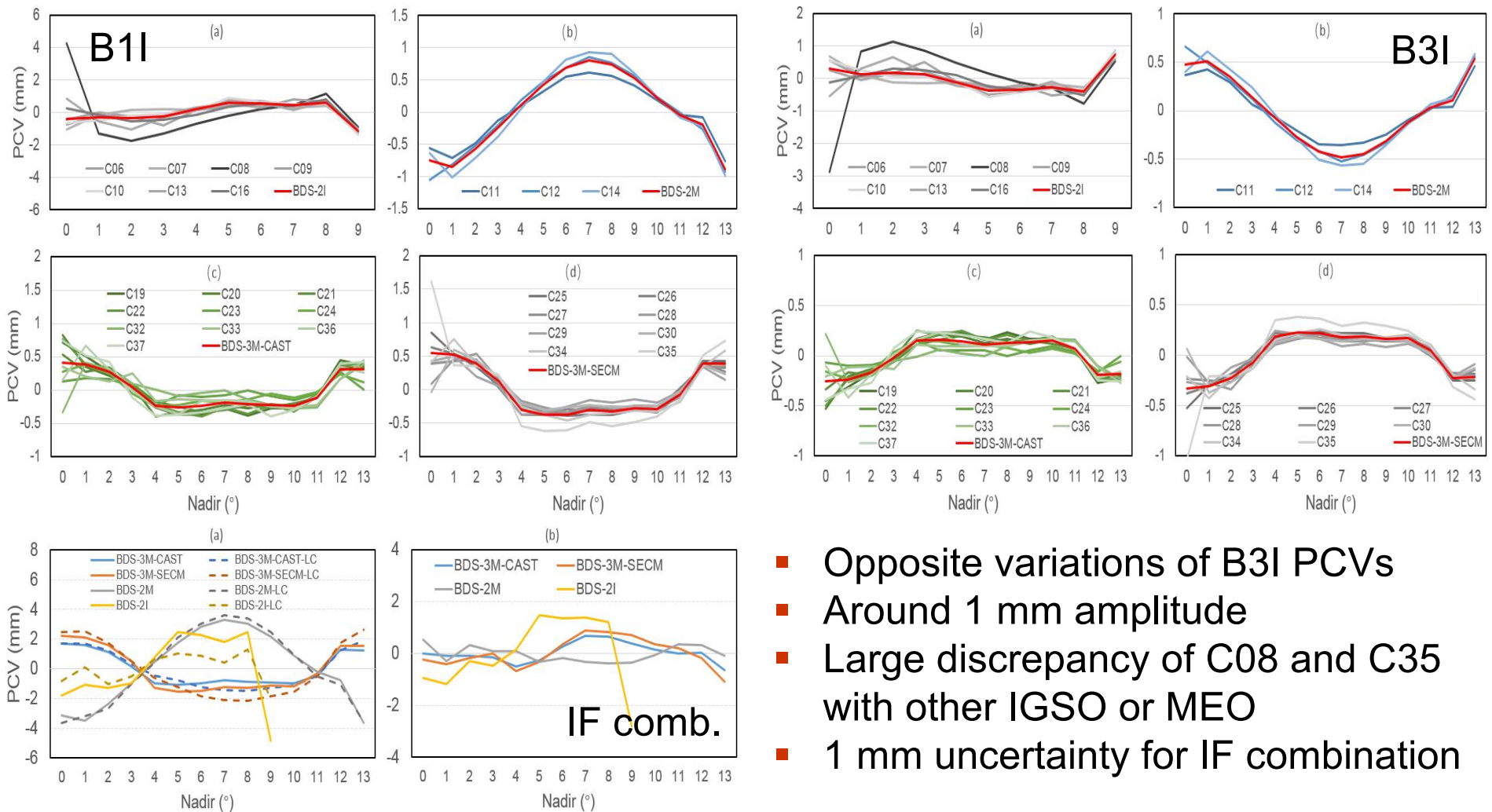


- Block-specific and nadir-dependent PCV values for B1I and B2I IF comb.

Nadir(°)	0	1	2	3	4	5	6	7
BDS-2I	-1.52	0.19	-0.09	-0.24	0.79	0.42	0.81	0.16
BDS-2M	-2.96	-3.50	-2.44	-1.52	-0.02	1.75	3.35	3.19
Nadir(°)	8	9	10	11	12	13	14	15
BDS-2I	0.94	-1.46	1.76					
BDS-2M	3.39	2.91	1.10	-0.04	-1.11	-4.11	-7.10	-8.60

Raw PCVs

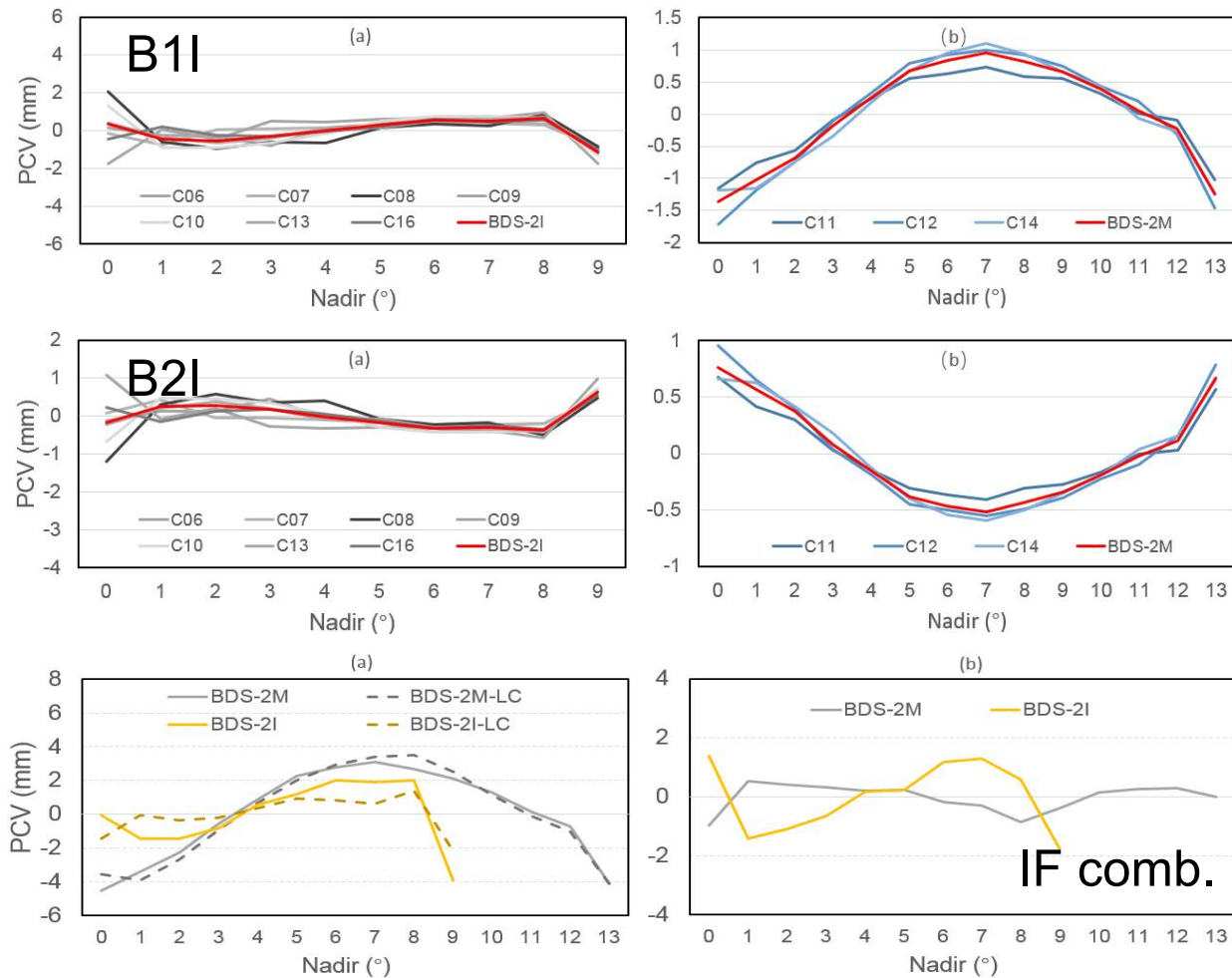
- Dual-freq. raw data are processed directly with constraining the PCVs to the estimation of IF combinations of the dual-freq.



- Opposite variations of B3I PCVs
- Around 1 mm amplitude
- Large discrepancy of C08 and C35 with other IGSO or MEO
- 1 mm uncertainty for IF combination

Raw PCVs

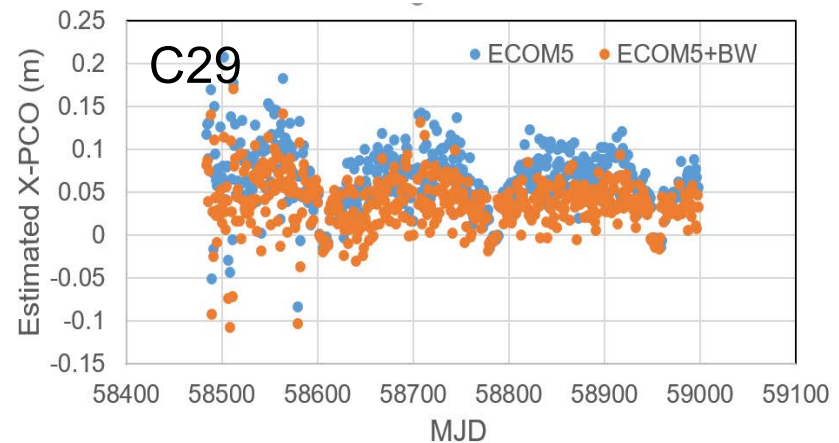
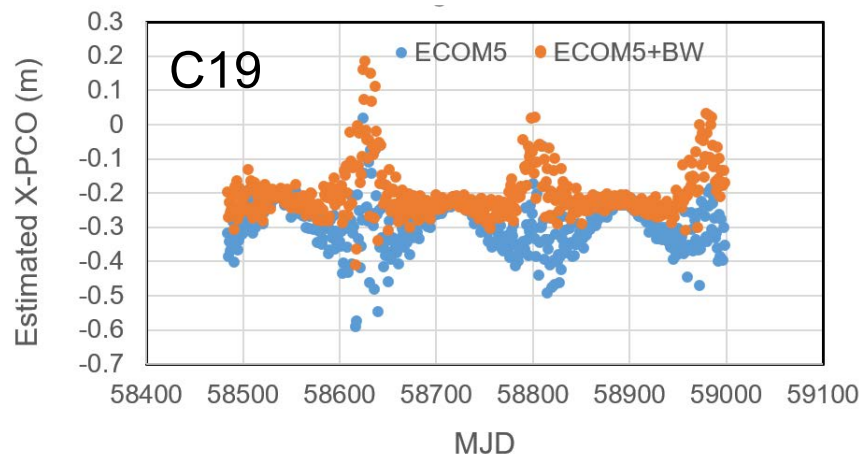
- Dual-freq. raw data are processed directly with constraining the PCVs to the estimation of IF combinations of the dual-freq.



- The consistency of B1I PCVs from different dual-freq. obs. is within 0.2 mm for IGSO and MEO, except for 0° up to 0.6 mm
- Better than 1 mm consistency for IF comb. PCVs estimated with raw or IF obs. for MEO, and lower than 2 mm achieved for IGSO

Solar radiation pressure on BDS orbit and PCO

- Proper modeling of the SRP is a prerequisite for an accurate determination of PCO values

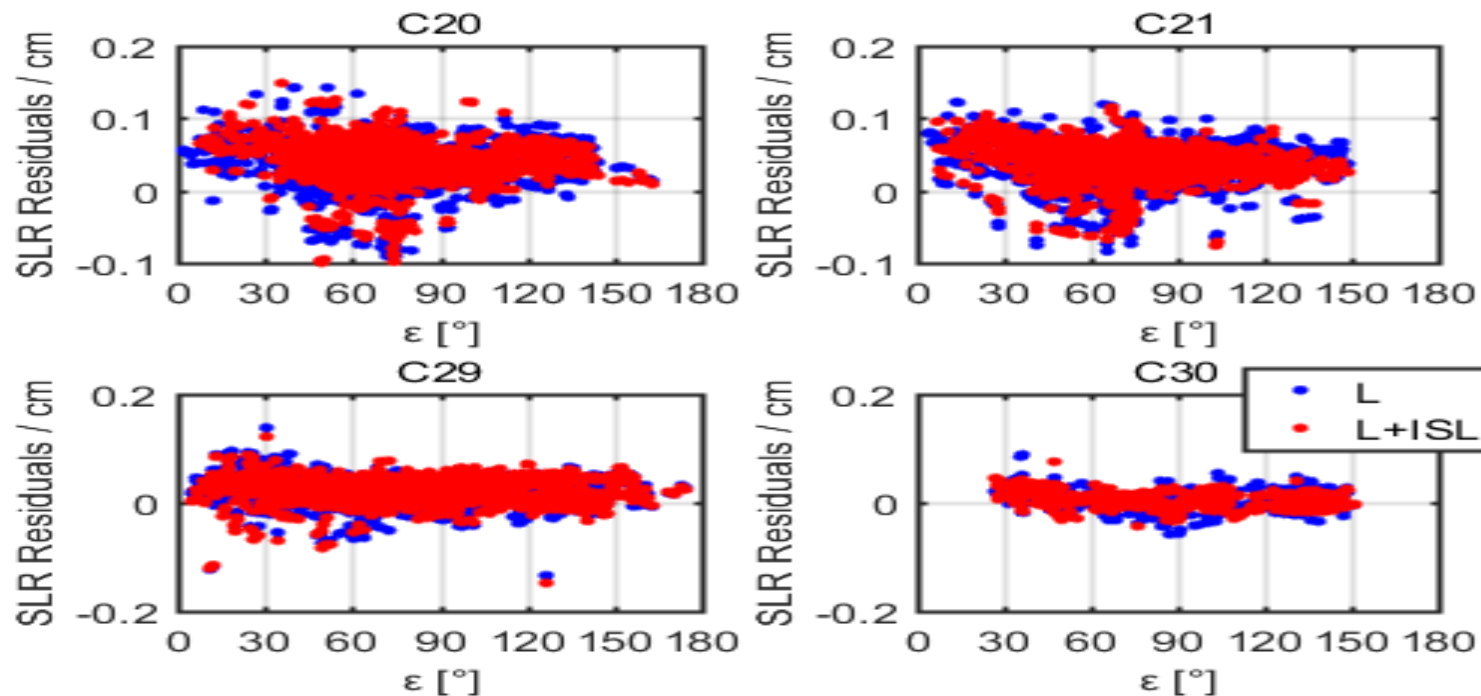


- Box-wing model based on the adjusted optical properties used for BDS-3 satellite groups with modeling antenna trust as well as albedo

Satellite Group	#1	#2	#3	#4
CAST MEO	C19-C24	C32, C33	C36, C37 C41, C42	C45, C46
SECM MEO	C25, C26	C27-C30	C34, C35	C43, C44
IGSO	C38, C40	C39		

Orbit validation

- SLR validation for the orbit solutions based on ground L-band or combination with ISL data

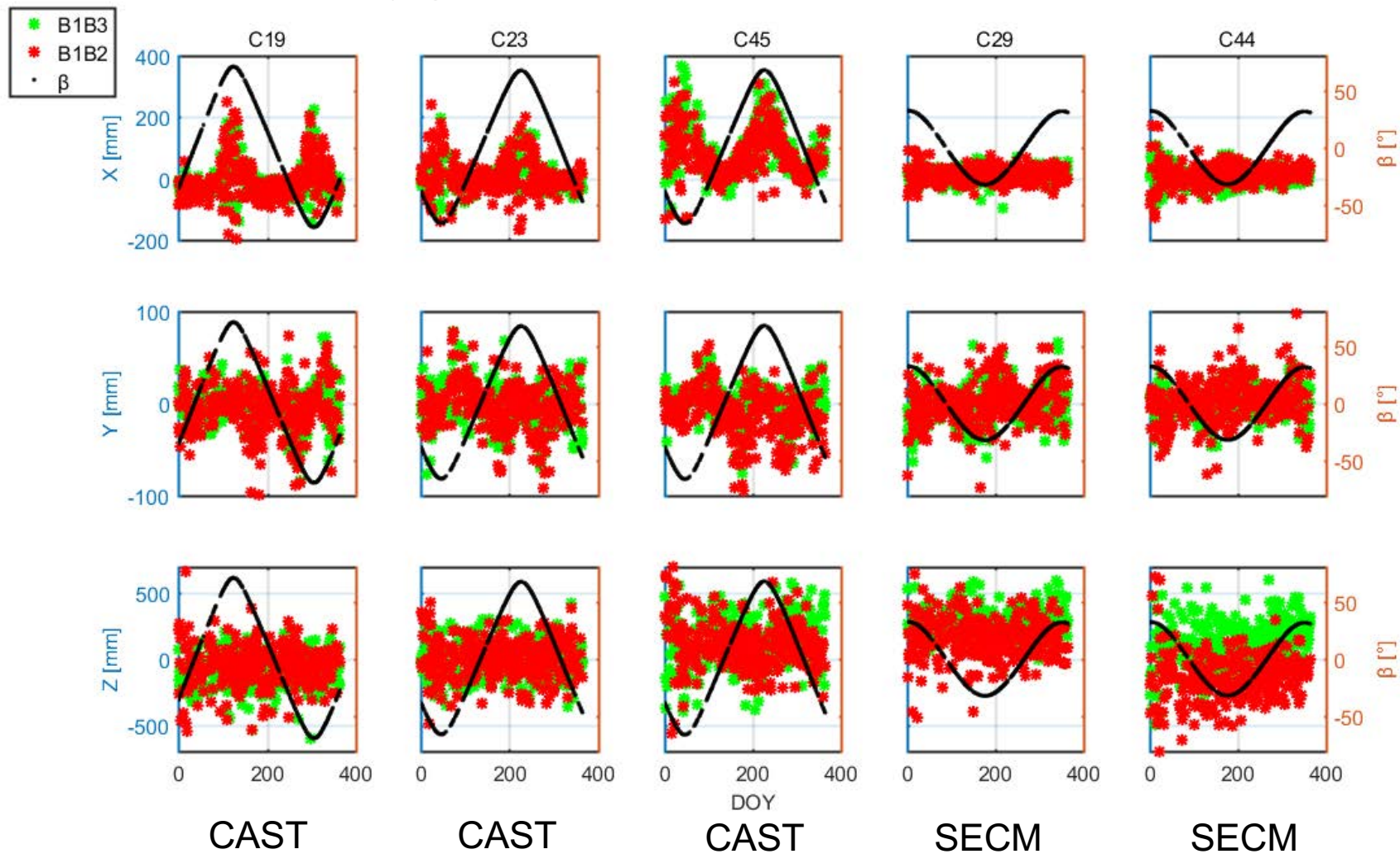


CPRN	L			L+ISL		
	Bias	STDev	RMS	Bias	STDev	RMS
C20	3	2.8	4.2	3.8	2.3	4.4
C21	3.3	2.7	4.3	3.8	2.3	4.3
C29	2	2.3	3.2	2.4	2.2	3.2
C30*	0.1	2.1	2.2	0.01	1.6	1.7

* DOY 160-238, 2020

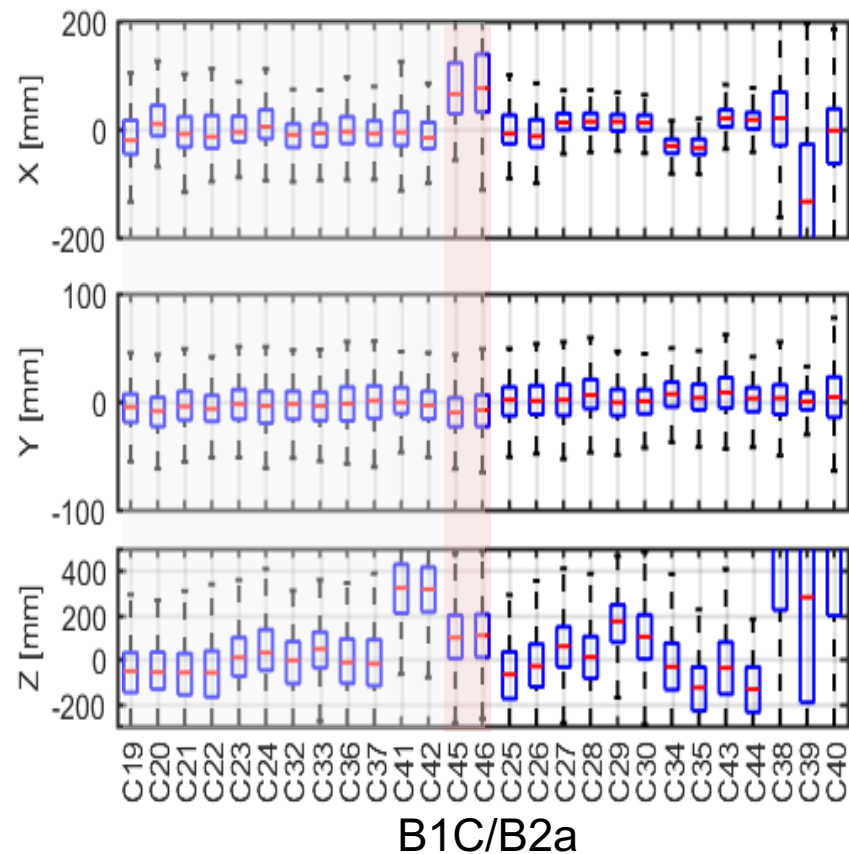
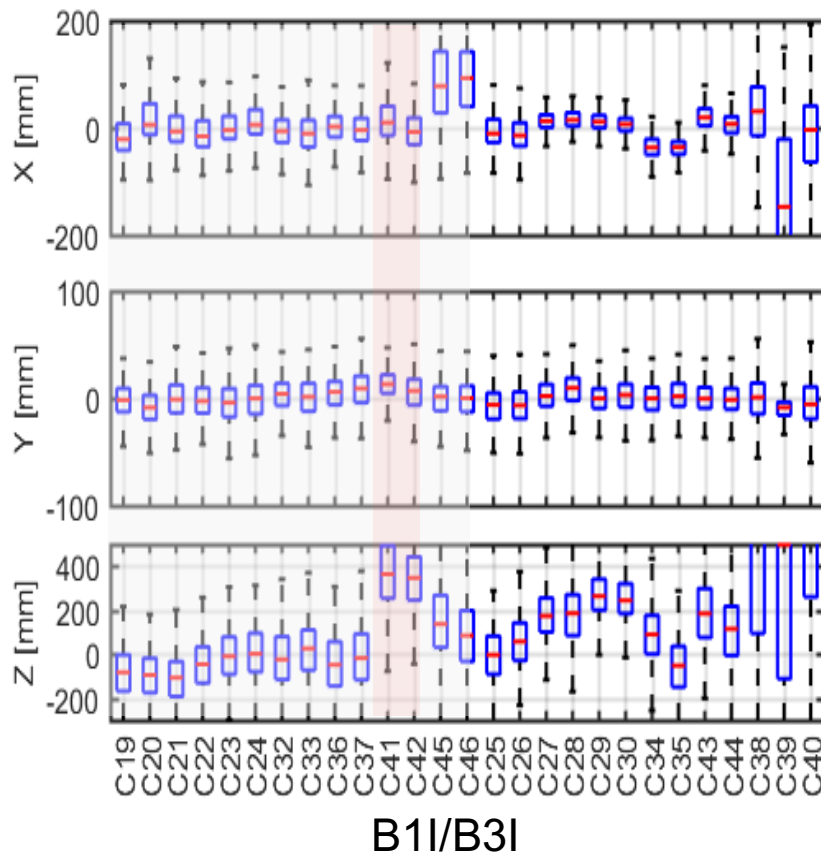
PCO estimation in IGS14 frame

- Time series of corrections to the disclosed values
 - More scatter due to BDS only solutions
 - Inconsistency ground calibration values of B1, B2, B3 for SECM



PCO estimation in IGS14 frame

- Satellite-specific corrections to the disclosed values
 - Large discrepancy for C41/C42 Z-PCO, C45/C46 X-PCO (CAST)
 - Up to meter differences for Z-PCO of IGSO satellites
 - Scatter estimation for SECM satellites
 - Stable estimation for C19-C24 as well as C32/C33, C36/C37



Estimated PCO values in IGS14 frame

PRN	B1I/B3I			B1C/B2a		
	X	Y	Z	X	Y	Z
C19'	-214	-12	1936	-212	-11	1918
'C20'	-198	-14	2001	-201	-11	1987
'C21'	-196	-8	1949	-201	-5	1940
'C22'	-207	-12	1973	-202	-13	1959
'C23'	-205	-7	2007	-207	-2	1971
'C24'	-193	-6	2056	-197	-4	2054
'C32'	-185	-6	2036	-195	-7	1979
'C33'	-196	-10	2052	-198	-9	1992
'C36'	-189	-11	1830	-193	-13	1817
'C37'	-198	-8	1854	-203	-12	1839
'C41'	-175	-6	1925	-191	-13	1855
'C42'	-206	-7	1904	-207	-12	1863
'C45'	-196	-9	2093	-208	-14	1971
'C46'	-187	-6	2047	-188	-9	1961
'C25'	74	-11	1102	79	-8	1032
'C26'	68	-12	1177	70	-5	1079
'C27'	39	-3	1296	39	-4	1175
'C28'	40	3	1293	40	2	1125
'C29'	38	-10	1404	40	-7	1284
'C30'	34	-5	1348	39	-6	1191
'C34'	53	-10	1205	58	-2	1081
'C35'	51	-8	1049	55	-6	971
'C43'	69	-7	1283	68	1	1052
'C44'	59	-9	1207	67	-6	960
'C38'	-48	-310	3149	-52	-310	3094
'C39'	-350	-312	3191	-308	-303	2660
'C40'	-81	-307	3330	-82	-303	3087

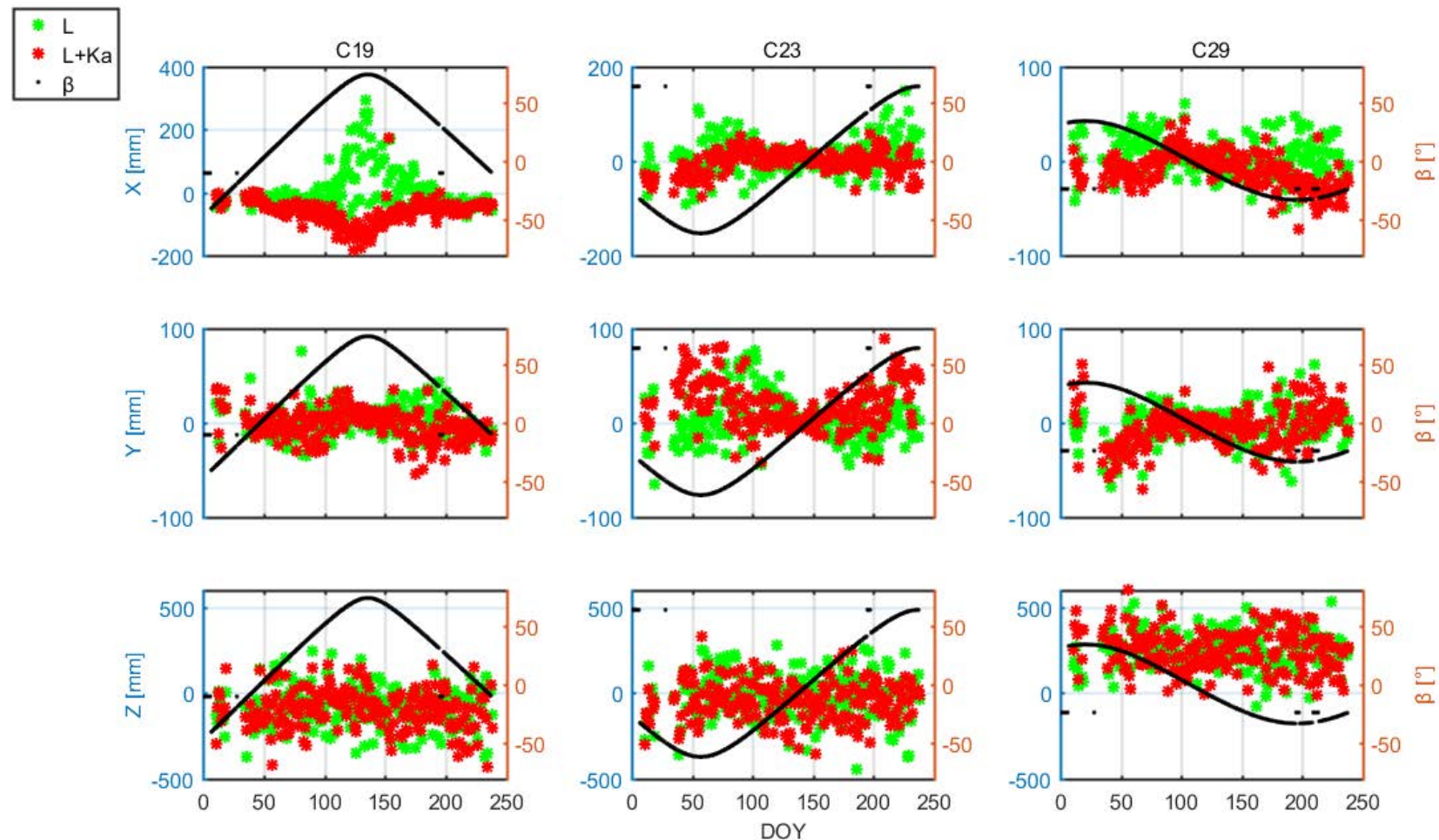
Unit: mm

8 CAST
MEOs

- B1I/B3I Z-PCO differences w.r.t CSNO released values
 - ✓ CAST: 32.4 mm
 - ✓ SECM: 125.3 mm
 - ✓ 8 CAST: -28.4 mm
- B1C/B2a Z-PCO differences w.r.t CSNO released values
 - ✓ CAST: 44.2 mm
 - ✓ SECM: -10.3 mm
 - ✓ 8 CAST: -8.0 mm

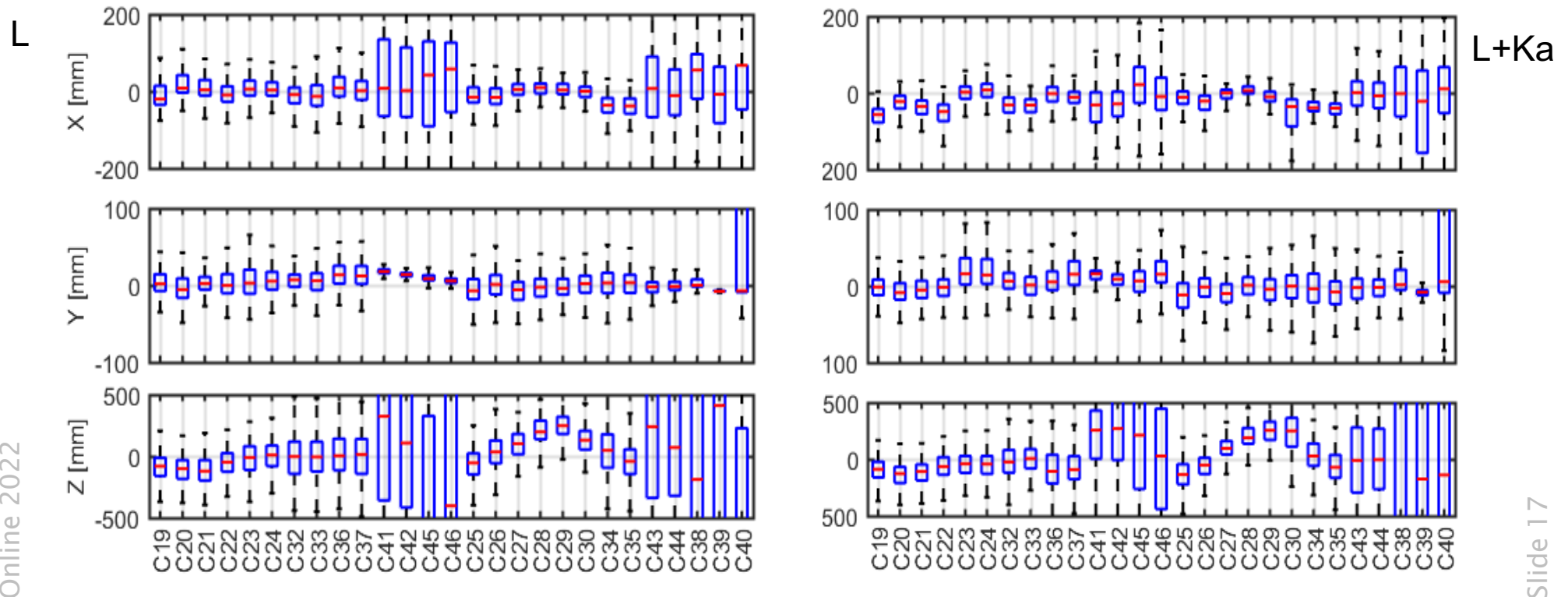
PCO estimation with L+ISL band in IGS14 frame

- Time series of corrections to the disclosed values
 - Stable estimation in horizontal PCO, particularly in high β regime
 - Slight improvement for Z-PCO estimation



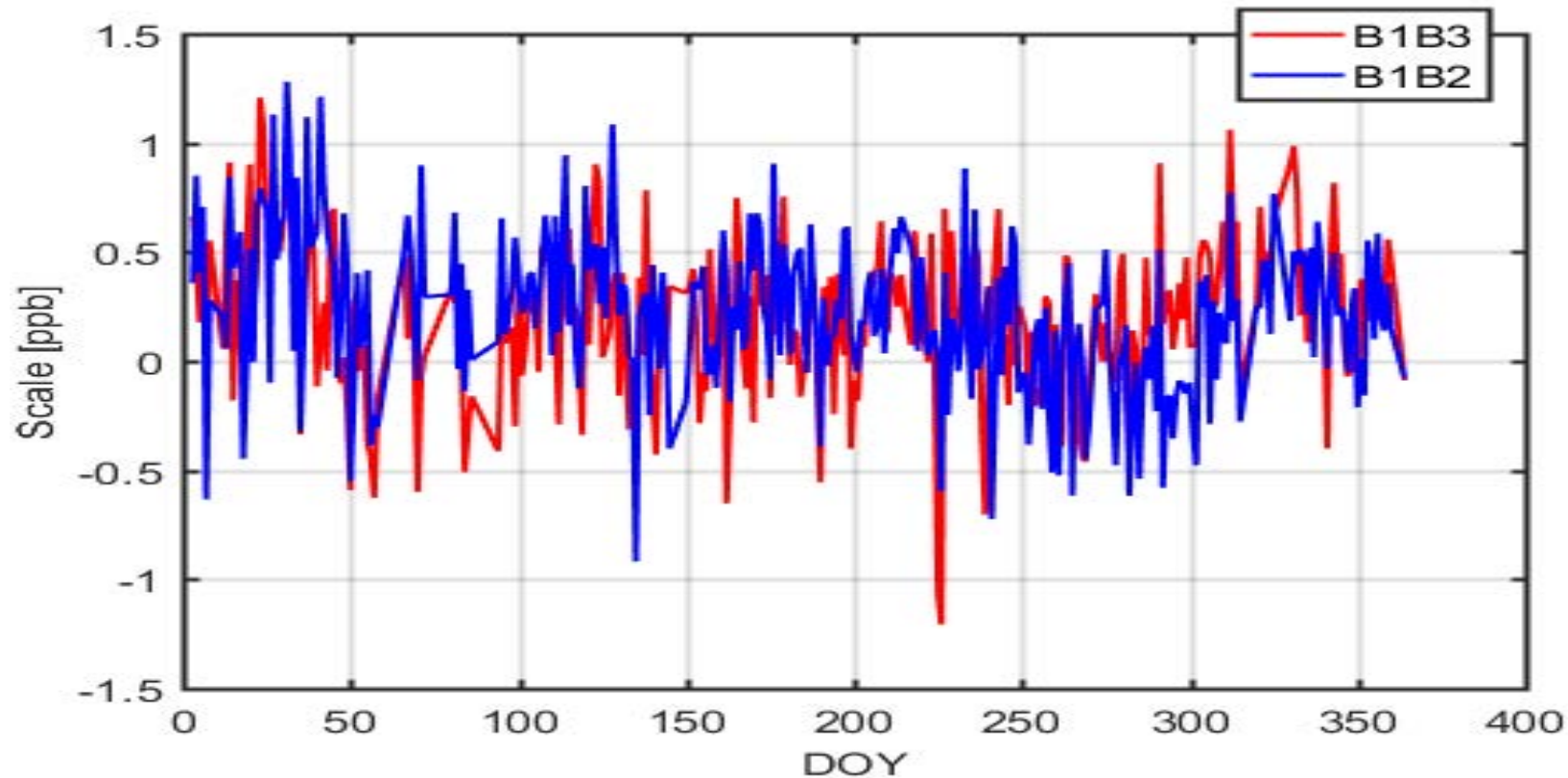
PCO estimation with L+Ka band

- Satellite-specific corrections to the disclosed values
 - Less data for satellites beyond C37, resulting in low quality of estimation (DOY 10-238, 2020)
 - Improvement for X- and Z-PCO, particularly for C41/C42, C45/C46, C43/C44, and IGSO satellites
 - Bias up to 29 mm in Z-PCO with aid of ISL data



Consistency with scale of IGS14

- One-step BDS-3 only solution
 - 8 satellites (C21C22C23C24C32C33C36C37) PCO fixed
 - PCO for other satellites estimated with orbit and site coordinates
 - NNR constrain applied



B1I/B3I: 0.20 ppb; B1C/B2a: 0.21 ppb

Summary & remaining issues

- Ground and LEO onboard data used for PCV estimation
 - ✓ Extended and raw PCV
 - Raw PCVs to be extended and cover all frequencies
 - More LEO onboard BDS data
- Ground data used for PCO estimation of IGSO and MEO
 - ✓ Satellite-specific values derived with better SRP modeling
 - ✓ Suspicious quality of C41 and C42 as well as those from SECM
 - ✓ Meter-level discrepancy for IGSO
 - PCO for each single frequency
- Investigation on the scale of disclosed BDS-3 PCOs
 - ✓ Selection of satellite group
 - ✓ Consisted scale factor derived from B1I/B3I and B1c/B2a
 - ✓ A decent agreement with ITRF2014
 - Large discrepancy with scale of Galileo and GPS BLOCK III

References

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