Estimation of BDS-3 Differential Code Biases with Satellite Antenna PCO Corrections Applied

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The 2nd Symposium of IAG Commission 4

Agenda

- PCO corrections in DCB estimation
- Estimated BDS-3 DCBs with/without modeled PCOs
- Effects of estimated DCBs on stand/precise positioning
- Summary and conclusions

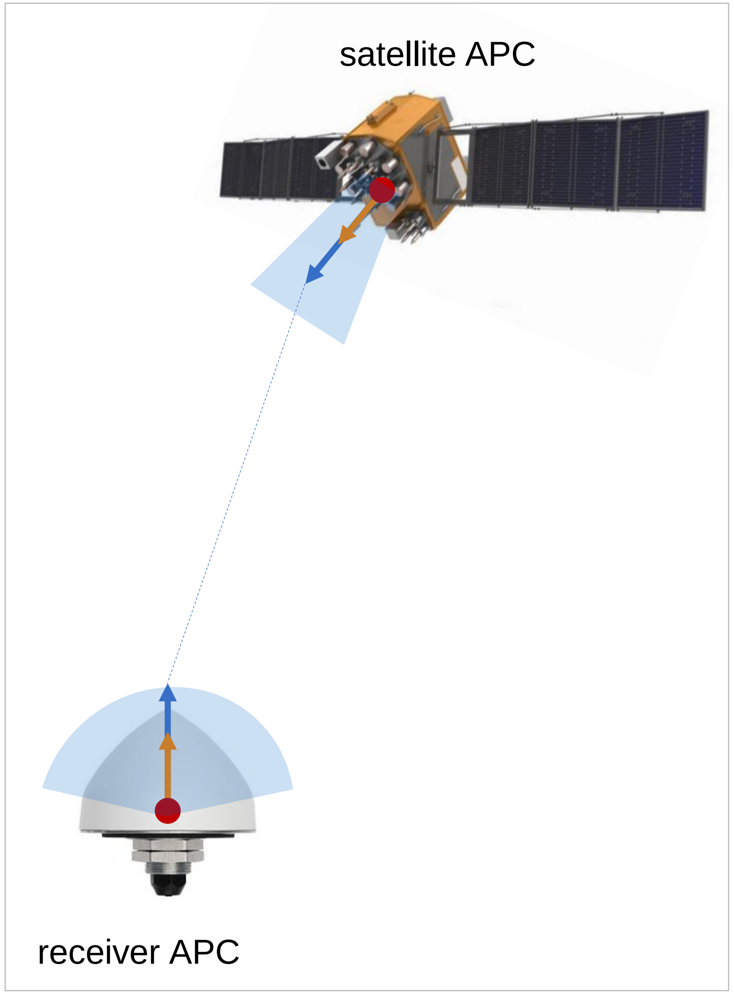
PCO corrections in DCB estimation

Satellite APC corrections in DCB estimation

- z-PCO mapping on LOS: 0.97-1.0
- z-PCO differences up to several decimeters
- satellite antenna PCOs requires to be modelled/corrected
- satellite phase center variations (PCV) can be ignored

Receiver APC corrections in DCB estimation

- z-PCO mapping on LOS: 0.0-1.0
- z-PCO differences limited to several centimeter
- receiver PCO/PCV can be ignored in DCB estimation



APC: Antenna Phase Center

PCO corrections in DCB estimation

DCB estimation with satellite PCO modeled/corrected

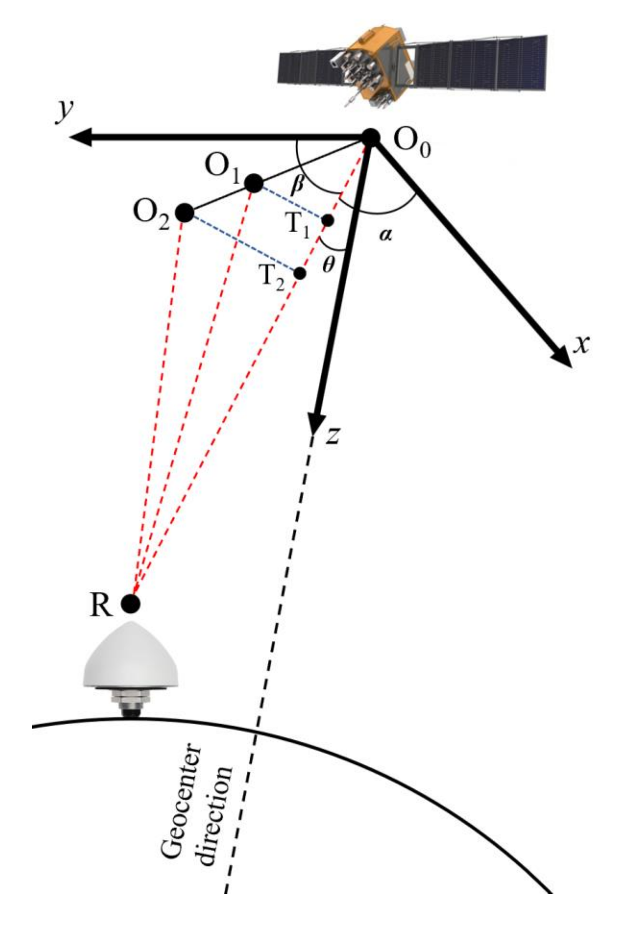
$$\Delta PCO^{sat}_{f_1-f_2} = PCO^{sat}_{f_1} - PCO^{sat}_{f_2} \approx \left|\overrightarrow{T_1T_2}\right|$$
$$= \cos\alpha\cdot(PCO_{x,f_1} - PCO_{x,f_2}) + \cos\beta\cdot(PCO_{y,f_1} - PCO_{y,f_2})$$
$$+\cos\theta\cdot(PCO_{z,f_1} - PCO_{z,f_2})$$
$$= \cos\theta\cdot(PCO_{z,f_1} - PCO_{z,f_2})$$

nearly zero

- The LOS distance is notably larger than satellite PCOs
- xy-PCO difference ~0.0
- z-PCO difference considered (smallest for Galileo, largest for QZSS)

CAST_C19	x-PCO	y-PCO	z-PCO
B1I	-200.0	0.0	1460.0
B3I	-200.0	0.0	1180.0

SECM_C25	x-PCO	y-PCO	z-PCO
B1I	40.0	-10.0	1100.0
B3I	40.0	-10.0	1090.0

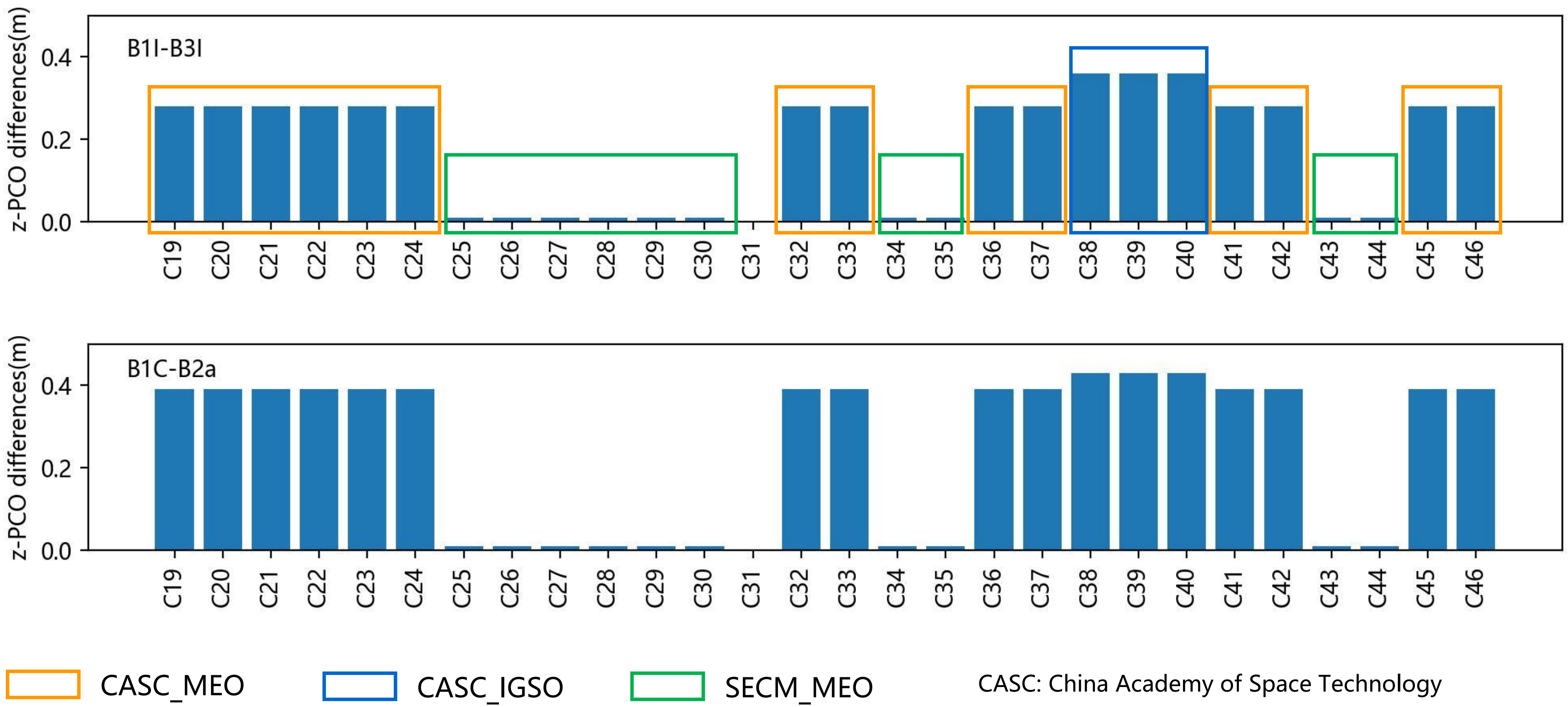


ranging difference between two frequencies cased by satellite PCOs

PCO corrections in DCB estimation

DCB estimation with satellite PCO modeled/corrected

- BDS-3 z-PCO differences of B1I-B3I and B1C-B2a GF combinations (from igs14_2196.atx)



CASC: China Academy of Space Technology
SECM: Shanghai Engineering Center for Microsatellites, CAS

PCO corrections in DCB estimation

DCB estimation with satellite PCO modeled (PCO-modeled DCB[1])

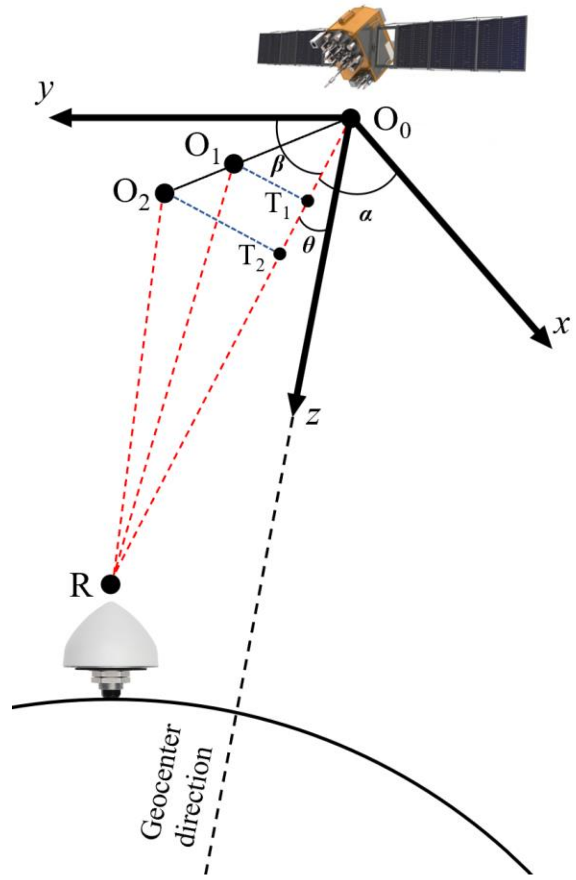
$$P_4 = (I_{f_1} - I_{f_2}) + (B_{f_1} - B_{f_2}) + (\varepsilon_{f_1} - \varepsilon_{f_2}) + (PCO_{f_1}^{sat} - PCO_{f_2}^{sat})$$

$$\approx 40.3 \cdot (\frac{1}{f_1^2} - \frac{1}{f_2^2}) \cdot sTEC + DCB_{f_1-f_2}^{sat+rec} + \Delta PCO_{f_1-f_2}^{sat}$$

$$\Delta PCO_{f_1-f_2}^{sat} \approx \left|\overrightarrow{T_1 T_2}\right|$$

- forming GF combination with satellite PCO modeled.
- using a local ionospheric VTEC modeling method for the jointly estimation of ionospheric and satellite-plus-receiver DCB parameters.
- applying a zero-constellation-mean constrict for the generation of satellite- and receiver-specific DCBs.

(Wang et al. JoGE, 2016, 2020)



ranging difference between two frequencies cased by satellite PCOs

PCO corrections in DCB estimation

DCB estimation with satellite PCO modeled (PCO-modeled DCB[1])

- CASDCB method for jointly local ionosphere and bias estimation

$$\begin{cases} P_{r,4}^{*,s} = c \cdot \mathbf{SPR}_r^s + 40.3 \cdot (f_2^2 - f_1^2) \cdot \mathbf{STEC}_r^s / f_1^2 f_2^2 \\ P_{r,4}^{*,s} = P_{r,4}^s - \cos\theta \cdot \Delta PCO_z \;, \quad \cos\theta \in [0.97, 1.00] \\ \mathbf{SPR}_r^s = b_{r,4} - b_4^s \end{cases}$$

VTEC model →

$$\mathbf{VTEC}_r^s(\varphi_d, \lambda_d, h) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{m_{\max}} \{E_{nm} \cdot \varphi_d^n \cdot \lambda_d^m\} + \sum_{k=0}^{k_{\max}} \{C_k \cos(k \cdot h) + S_k \sin(k \cdot h)\}$$

satellite- and receiver-specific DCBs →

$$\hat{\mathbf{X}}_{dcb} = (\mathbf{F}^{\mathrm{T}}\mathbf{F} + \mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}\mathbf{F}^{\mathrm{T}}\mathbf{Z}_{\mathbf{SPR}}$$

ΔPCO absorbed in the estimated DCBs

$$\Delta\mathbf{DCB}_{pco} = (\mathbf{F}^{\mathrm{T}}\mathbf{F} + \mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}\mathbf{F}^{\mathrm{T}} \cdot \Delta\mathbf{PCO}_z$$

(Wang et al. JoGE, 2016, 2020)

PCO corrections in DCB estimation

DCB estimation with satellite PCO corrected (PCO-corrected DCB[2])

- ignoring the time-varying z-PCO ($\cos\theta=1$)

$$DCB_{f_1-f_2}^{*,sat} = DCB_{f_1-f_2}^{sat} - \Delta DCB_{pco,f_1-f_2}^{sat} \quad \text{(Eq. 1)}$$

PCO-corrected DCB ($DCB_{f_1-f_2}^{*,sat}$)

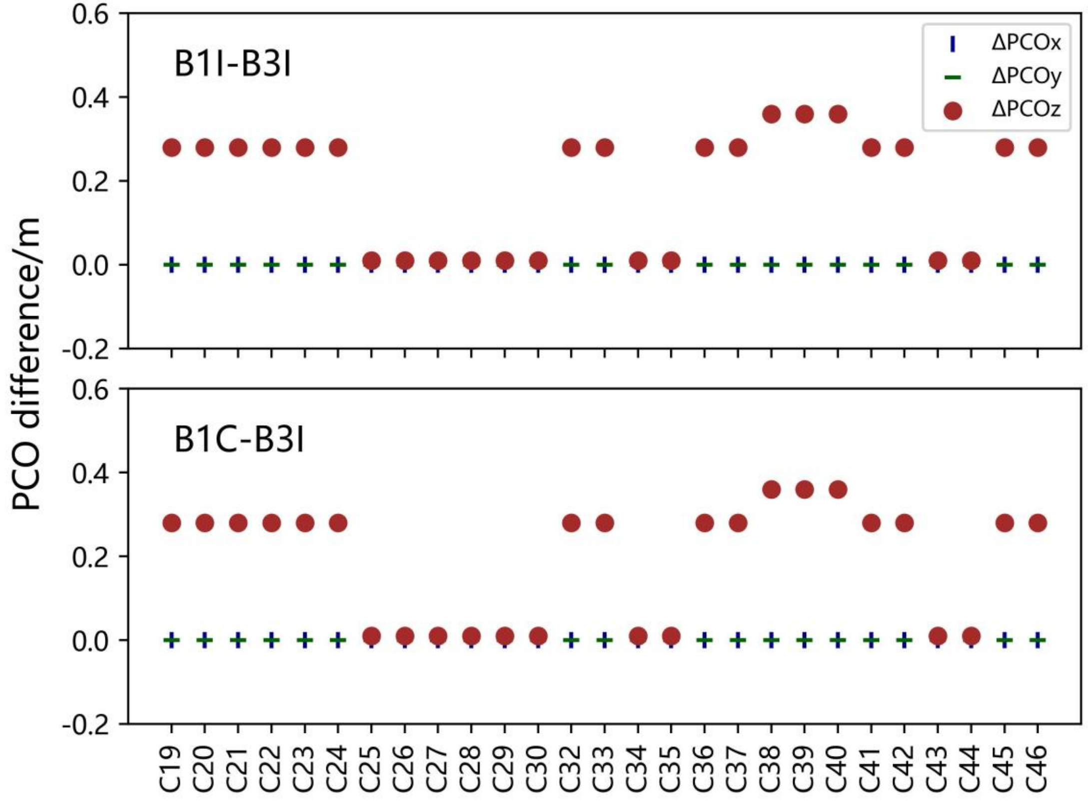
DCB without PCO corrections ($DCB_{f_1-f_2}^{sat}$)

DCB_{PCO} correction ($\Delta DCB_{pco,f_1-f_2}^{sat}$)

(Montenbruck et al. 2022)

Table 1 theoretical PCO corrections for B1I/B1C-B3I DCBs

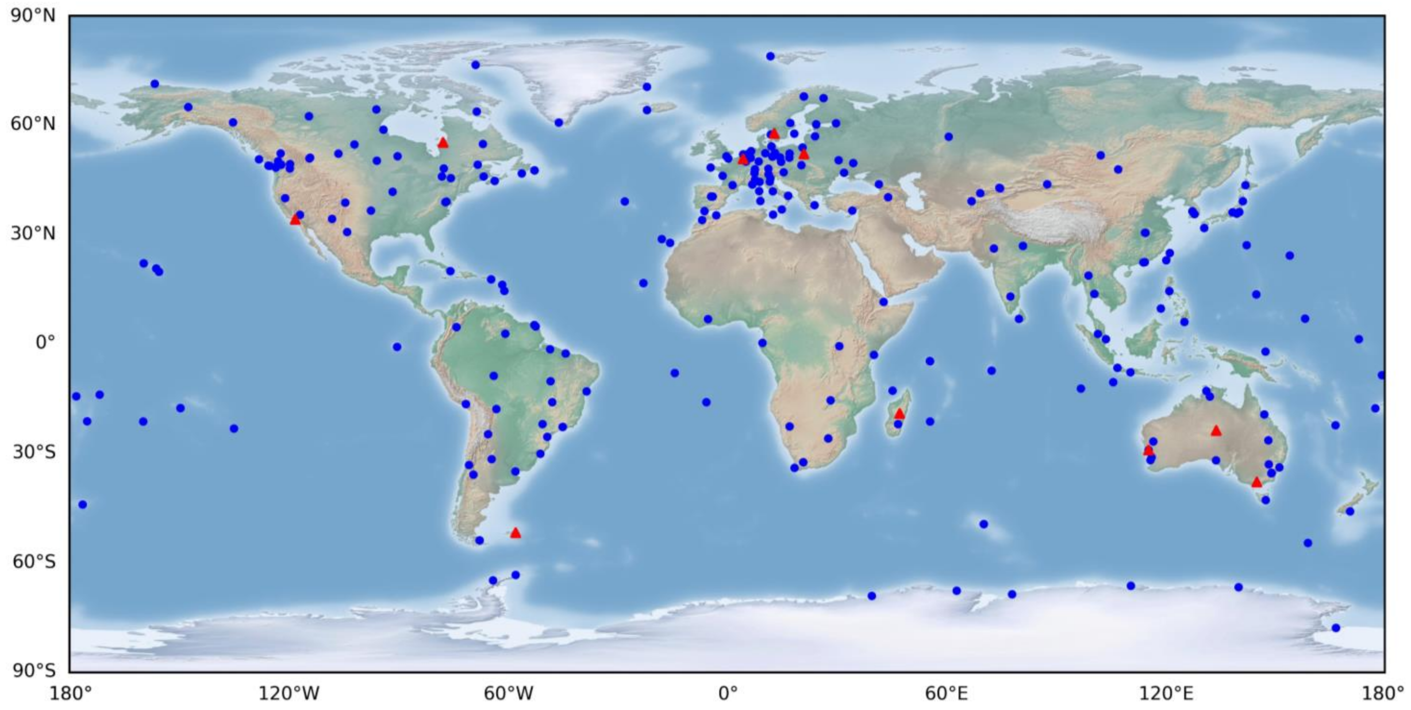
Satellite type	**ΔDCB_{PCO} (ns)**
CASC_MEO	-0.304
CASC_IGSO	-0.571
SECM_MEO	0.597



PCO differences for BDS-3 B1I-B3I and B1C-B3I GF combination (from igs14_2196.atx)

Estimated BDS-3 DCBs with/without modeled PCOs

DCB estimation using IGS-MGEX observation data

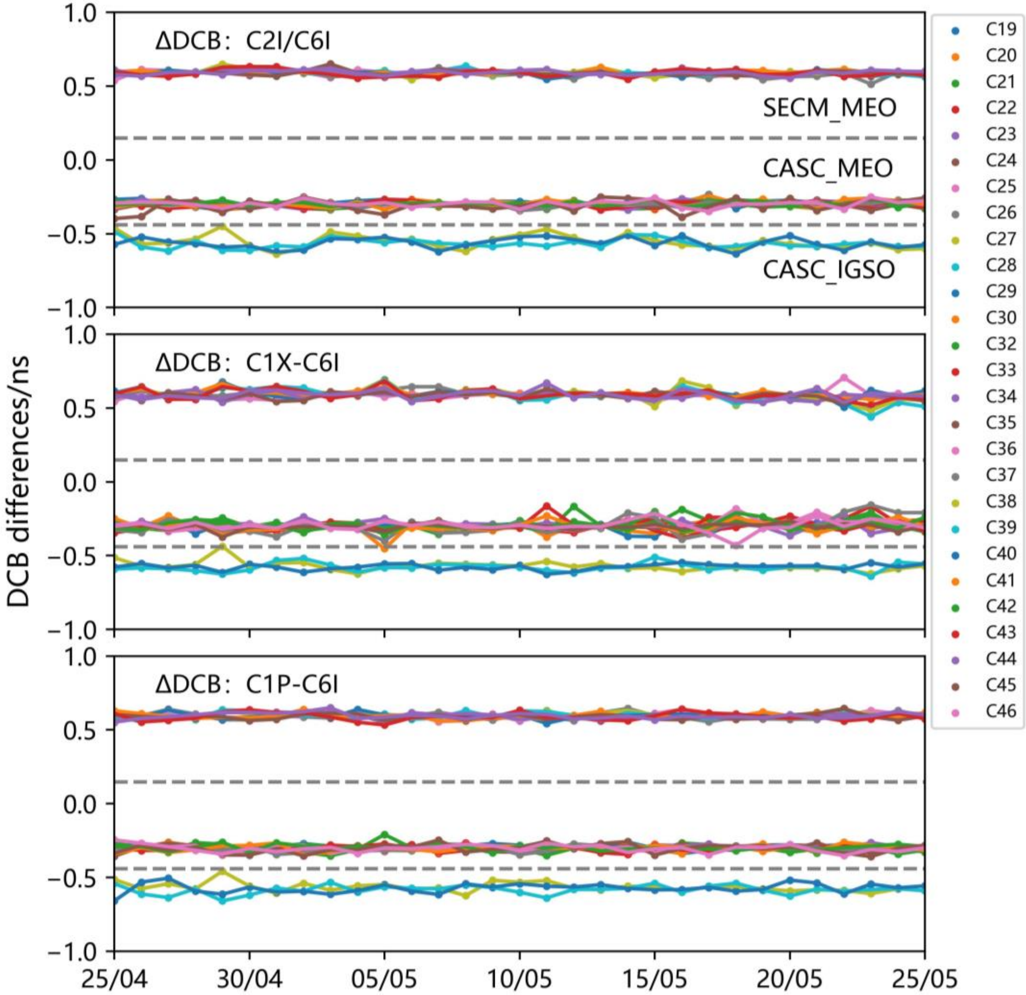


blue circles for DCB estimation with/without PCO corrections

red triangles for DCB validation in positioning

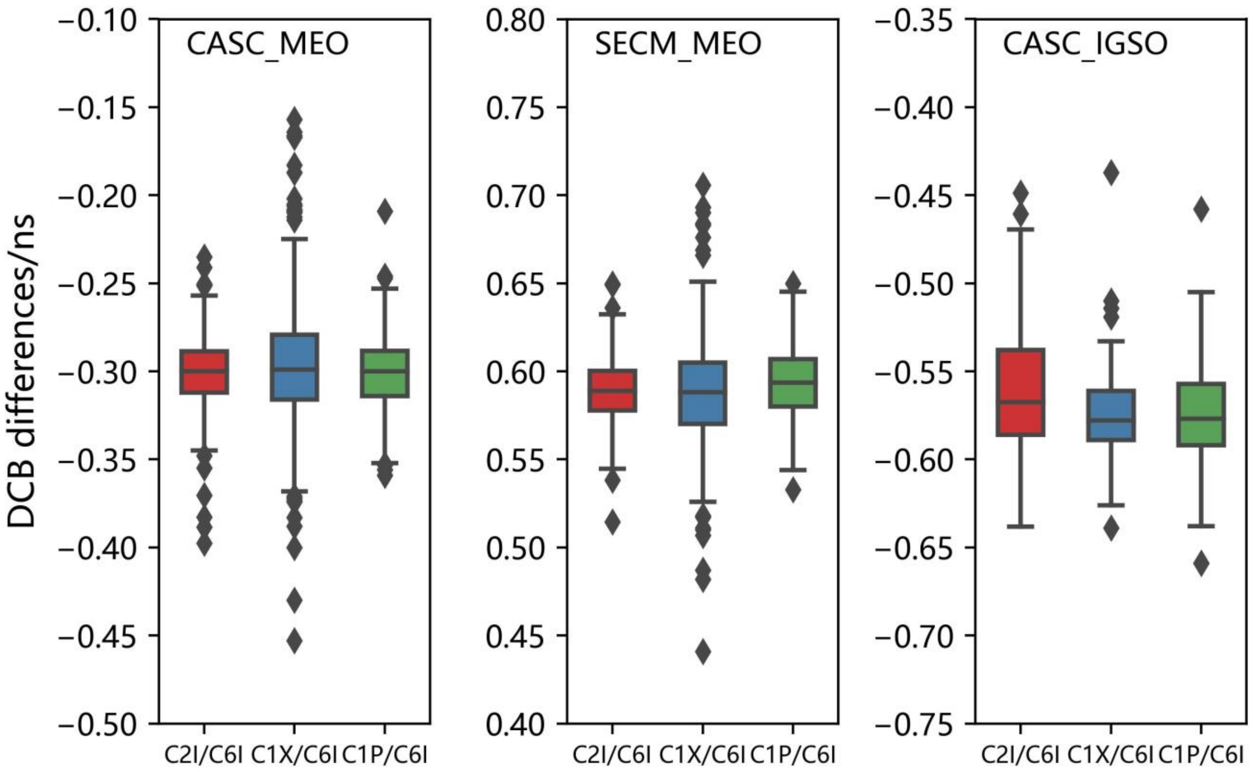
DCB	Station number	
	25/04	**25/05**
C2I-C6I	174	193
C1P-C6I	83	97
C1X-C6I	51	51

Estimated BDS-3 DCBs with/without modeled PCOs



Compared to theoretical PCO corrections in Table 1

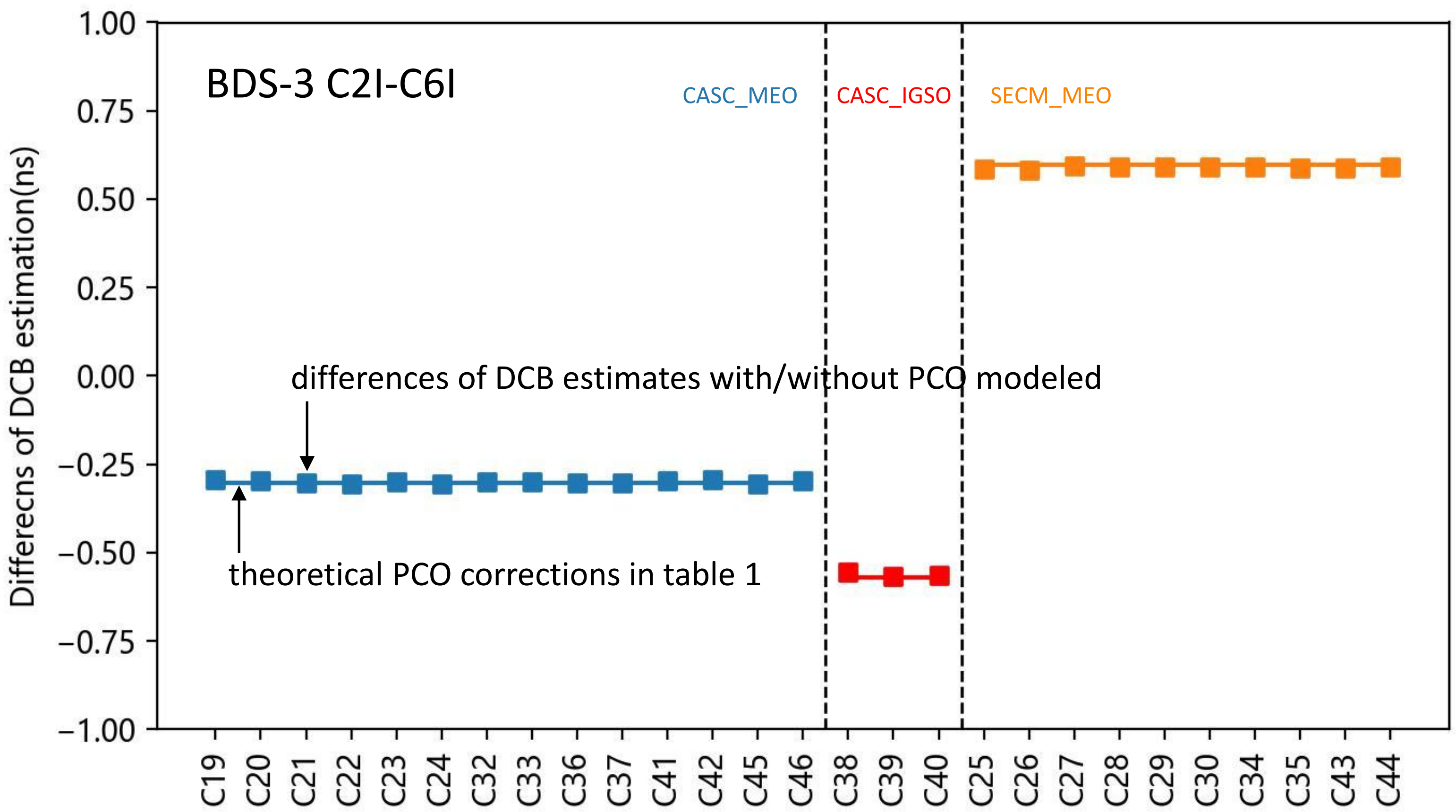
mean difference is within the range of 0.003-0.01 ns



STD of DCB difference series: 0.02-0.04 ns

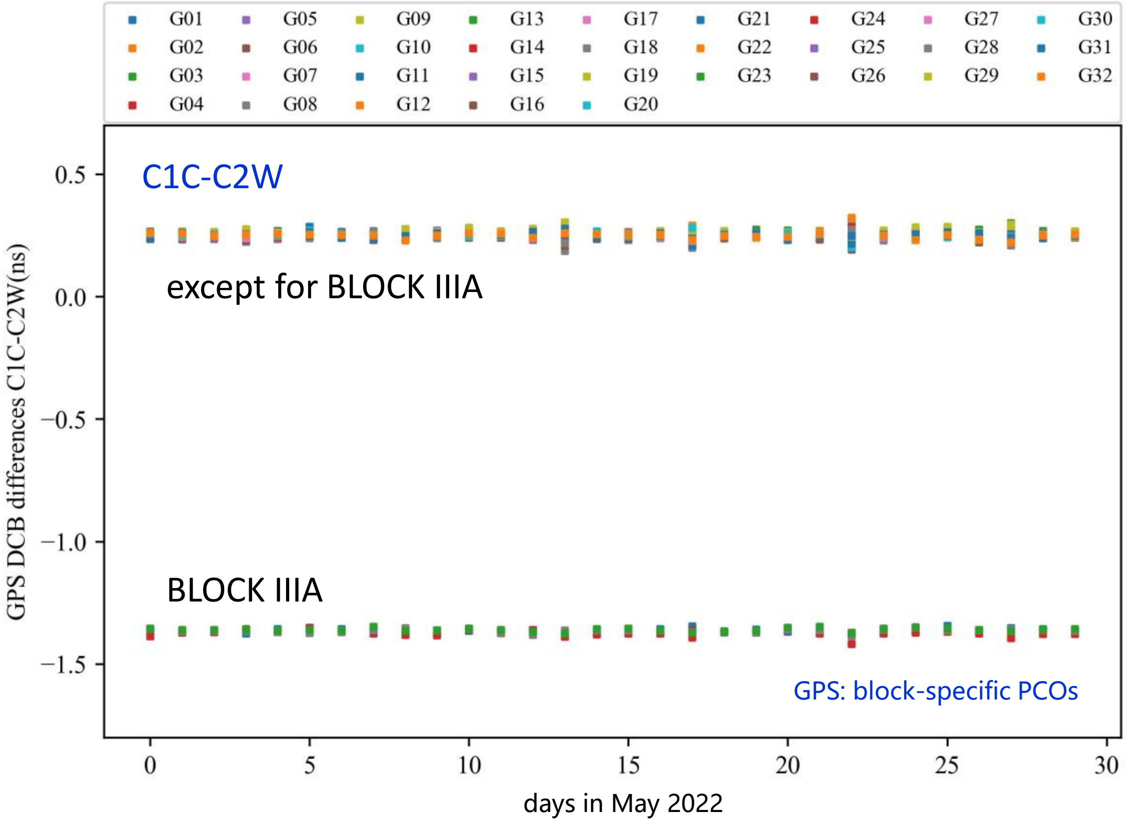
Estimated BDS-3 DCBs with/without modeled PCOs

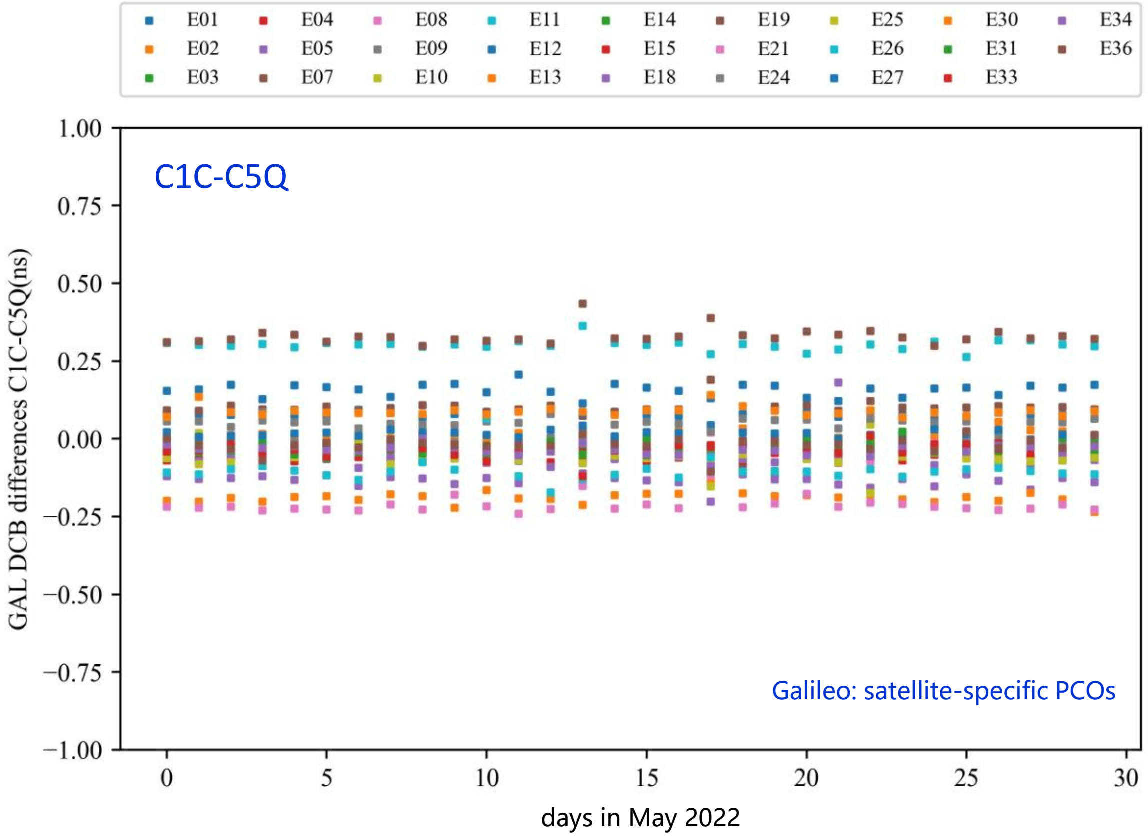
Differences of estimated DCBs with/without PCO modeled (May 2022)



Estimated GPS/GAL DCBs with/without modeled PCOs

Differences of estimated GPS/GAL DCBs with/without PCO modeled (May 2022)





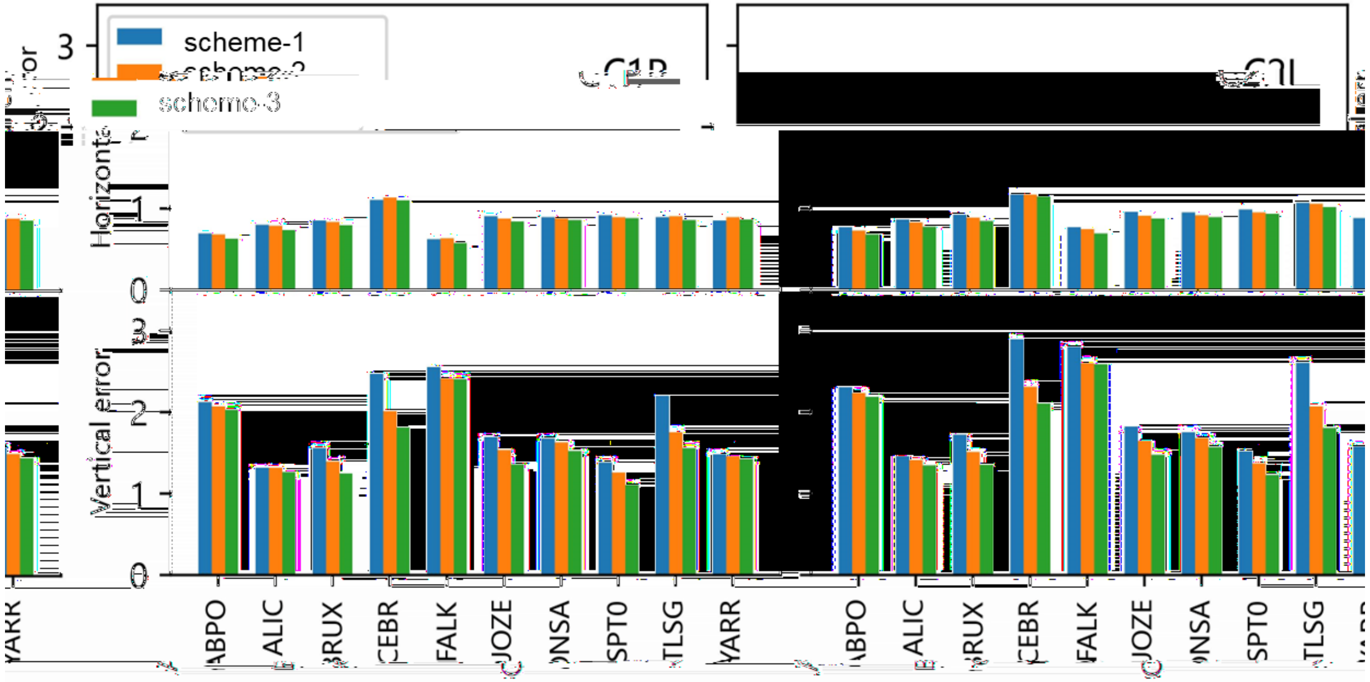
Multi-GNSS DCBs & OSBs with/without modeled PCOs

items	DCB/OSB without modeled PCOs	DCB/OSB with modeled PCOs
DCB file name	CAS0MGXRAP_yyyyddd0000_01D_01D_DCB.BSX	CAS1MGXRAP_yyyyddd0000_01D_01D_DCB.BSX
OSB file name	CAS0MGXRAP_yyyyddd0000_01D_01D_OSB.BIA	CAS1MGXRAP_yyyyddd0000_01D_01D_OSB.BIA
Satellite orbits	IGS combined broadcast ephemeris data	GBM rapid products
BDS-2 GDV model	Not applied	Not applied
Time latency	2 days	4 days
Data coverage	2013-now	August/2022-Now (extended to January/2022)
Data archive	CAS/IGN/CDDIS	CAS (ftp.gipp.org.cn/product/dcb/mgex/yyyy/)

Effects of estimated DCBs on stand/precise positioning

BDS-3 C1P/C2I "precise" single-frequency positioning (GFZ rapid orbits and clocks)

- scheme-1: estimated DCBs without PCO correction applied (i.e. CAS MGEX DCBs)
- scheme-2: PCO-corrected DCBs[2] following Eq. (1)
- scheme-3: PCO-modeled DCBs[1]



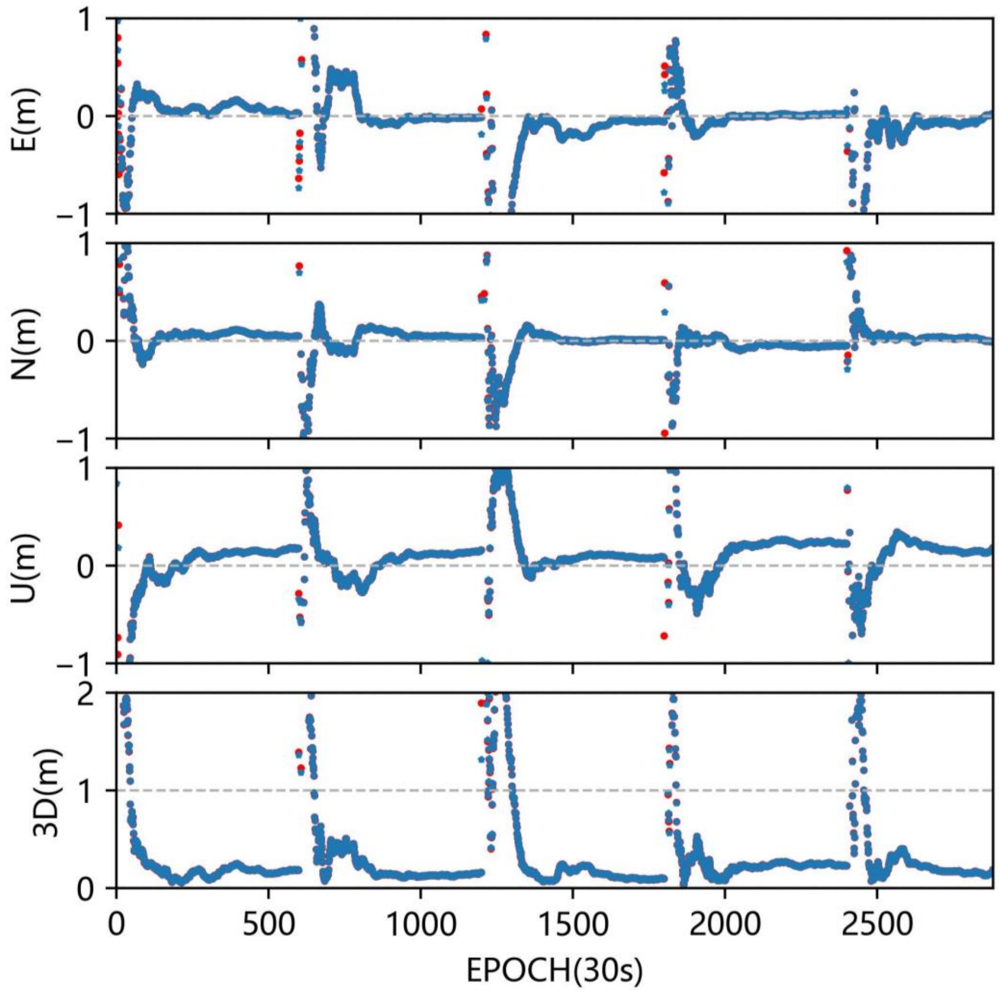
positioning improvement compared to scheme-1 (S-1, 95% percentile)

		C1P	C2I
S-2	H_95%	0.2%	3.0%
	V_95%	8.0%	9.5%
S-3	H_95%	4.8%	6.8%
	V_95%	14.2%	15.6%

Effects of estimated DCBs on stand/precise positioning

BDS-3 B1I single-frequency PPP (GFZ rapid orbits and clocks)

station : FFMJ
year : 2022
doy : 220
signal : BDS-3 B1I

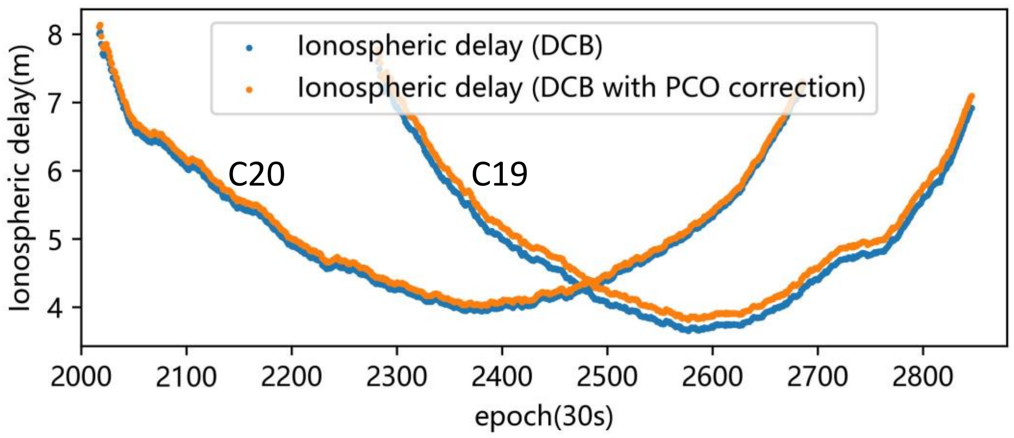


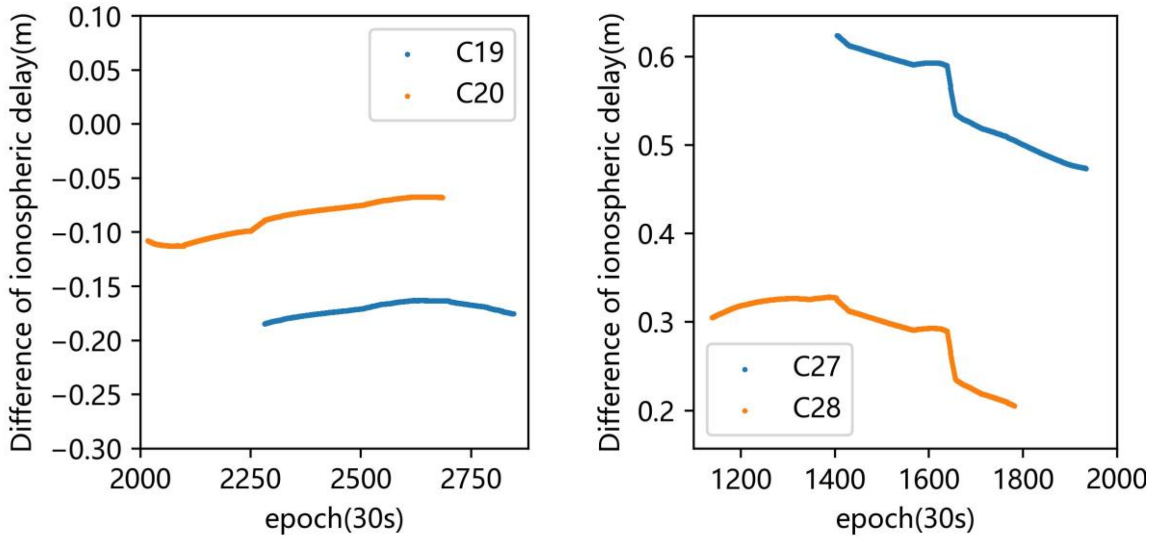
- For SF-PPP, positioning parameters not affected by PCO errors in DCBs (i.e., $\Delta\mathbf{DCB}_{pco}$)
- Such errors absorbed in receiver clock (common part), ambiguity and ionosphere parameters (satellite-specific part)

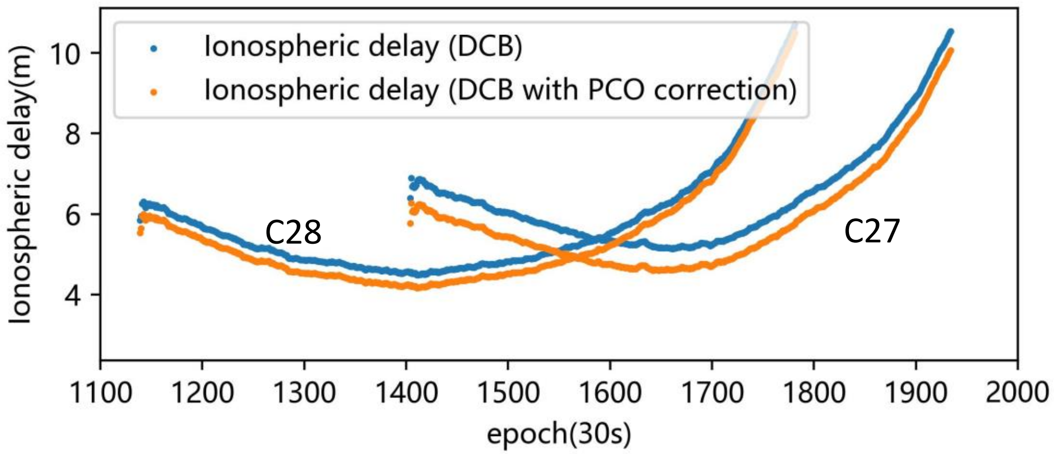
● DCB estimates without modeled PCOs
● DCB estimates with modeled PCOs

Effects of estimated DCBs on stand/precise positioning

BDS-3 B1I single-frequency PPP (GFZ rapid orbits and clocks)







selected satellites	mean difference(m)
C19 (CASC_MEO)	-0.169
C20 (CASC_MEO)	-0.087
C27 (SECM_MEO)	0.532
C28 (SECM_MEO)	0.263

Summary and conclusions

- Effects of satellite PCOs on the estimated DCBs were analyzed for BDS, GPS and Galileo (PCO-modeled DCBs vs. PCO-corrected DCBs).
- The analysis of BDS-3 B1I/B1C-B3I DCB estimates with/without modeled PCOs proofs the consistent modeling of PCOs in the estimated DCBs.
- BDS-3 C1P/C2I “precise” standard positioning further verifies the good consistency between the estimated DCBs with modeled PCOs and precise orbit/clock products.
- When extracting ionosphere information from SF-PPP, the largest difference caused by DCBs with/without modeled PCOs reaches ~0.5 m (from BDS-3 B1I SF-PPP analysis) .
- Multi-GNSS DCB/OSB products with modeled PCOs are publicly accessible from CAS ftp site (data coverage: August/2022-Now, ftp://ftp.gipp.org.cn/product/dcb/mgex/yyyy/)