Estimation of antenna phase center offset for BDS IGSO and MEO satellites

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1. background

- Antenna phase center offsets (PCOs), which are not only the error source but also translation-parameters of the center of mass, play an important role in precise positioning. On the other hand, inaccurate phase center corrections will also lead to the uncertainty of the reference frame and degrade the performance of the orbit product.
- For BDS, phase center corrections of IGSO and MEO satellites were estimated by ESA/ESOC (Dilssner et al., 2014) and Wuhan university (Guo et al., 2016). However, there were significant differences between the two estimations of the z-offset for IGSO, and satellites that prevented incorporation of these results into igs08.atx. (Montenbruck et al. 2017).
- Thus, it is necessary to further study the accurate estimation of PCOs for BDS satellites, especially for IGSO satellites.

2. PCOs parameters model

The phase center offset correction for a given unit vector $\vec{e}_r = (sin\alpha sin\eta, cos\alpha sin\eta, cos\eta)$ of the observation can be expressed as

$$\Delta\rho(\alpha,\eta) = -\vec{P}\cdot\vec{e}_r$$
$$= -dx\cdot sin\alpha sin\eta - dy\cdot cos\alpha sin\eta - dz\cdot cos\eta$$

η is the nadir angle and α is the azimuth in body-fixed sy stem when viewing from the station; dx, dy, and dz are x-offset, y-offset, and z-offset of PCOs, respectively.

3. PCOs estimation for BeiDou-2 B1 & B2 combination

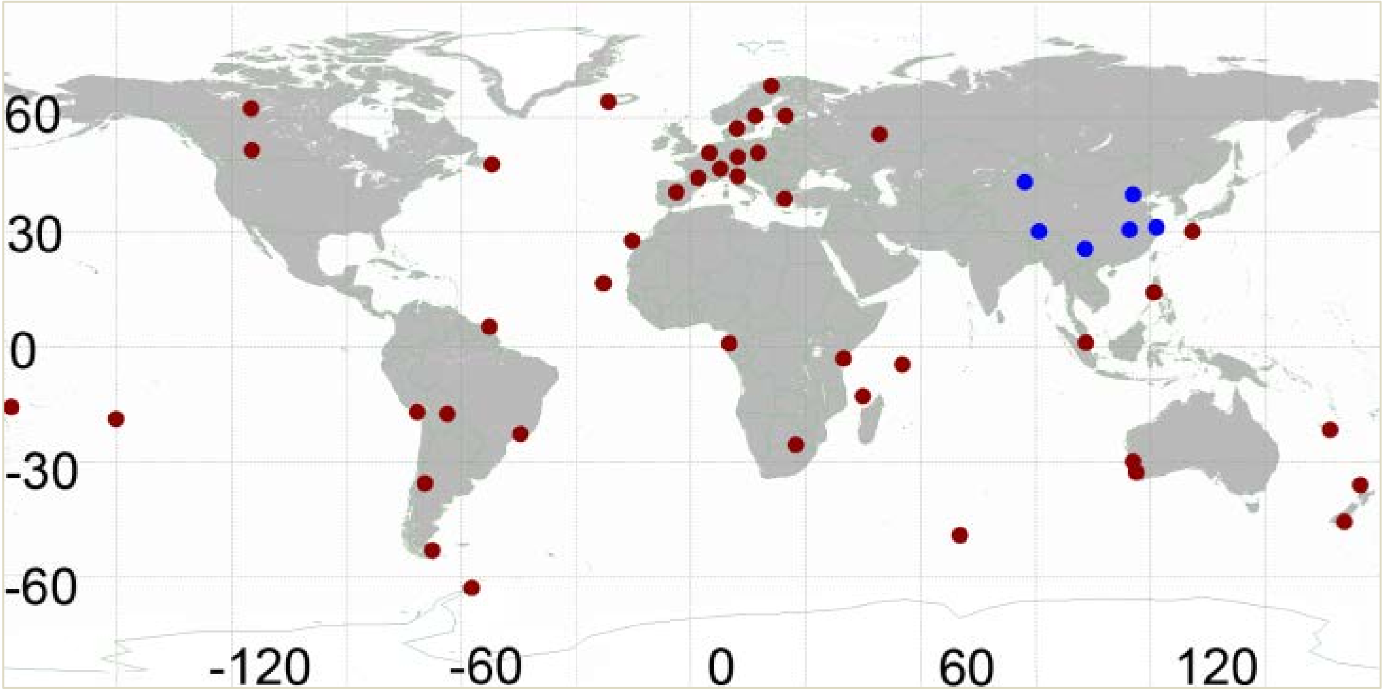
3.1 PCOs estimation for BeiDou-2

Strategies for data processing

Items	Description
Number of stations	**50** stations
Time interval	From 1 January to 31 December **2015**
observation	**Zero-difference** GPS/BDS phase and code observations
Sampling rate	300 s
Elevation cut-off angle	3°
weighting	Elevation-dependent; GPS:BDS = 4:1;
Stations coordinates	Fixed to an IGS week-solution, others from GPS PPP;
orbits	**72** hours arcs; 6 initial positions and velocities;
Solar radiation model	**ECOM1** VS **ECOM2**; No a priori model;
Satellites PCOs	initial values: **(600,0, 1100) mm;** Constraints are **(10, 1, 10) m;**
Satellites PVs	Set zero for all BDS satellites;
Receiver PCOs and PVs	using L1 and L2 for B1 and B2

3.1 PCOs estimation for BeiDou-2

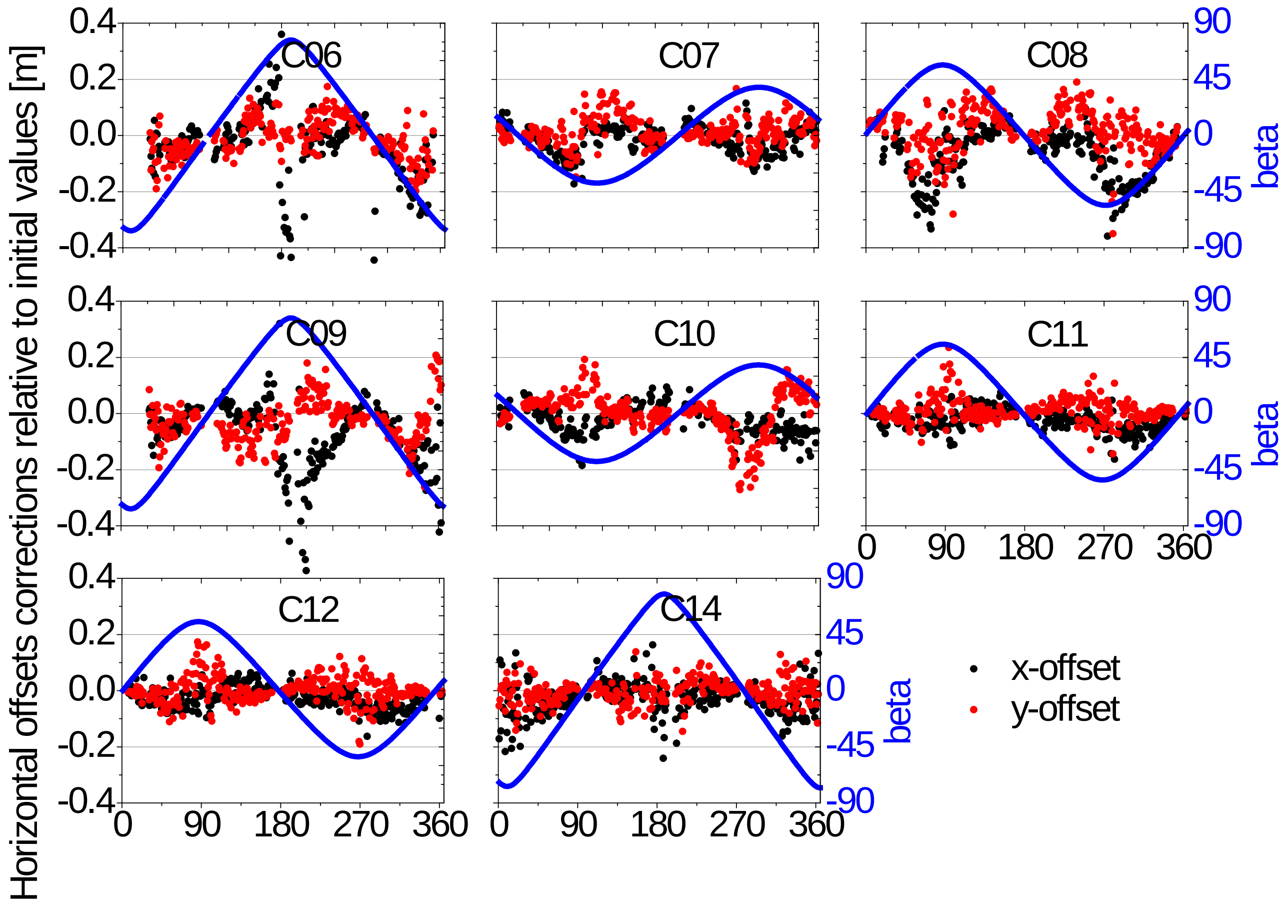
Distribution of the selected stations



Distribution of the selected stations. **Red** cycle stations are from MGEX and **blue** cycle stations are from iGMAS.

3.1 PCOs estimation for BeiDou-2

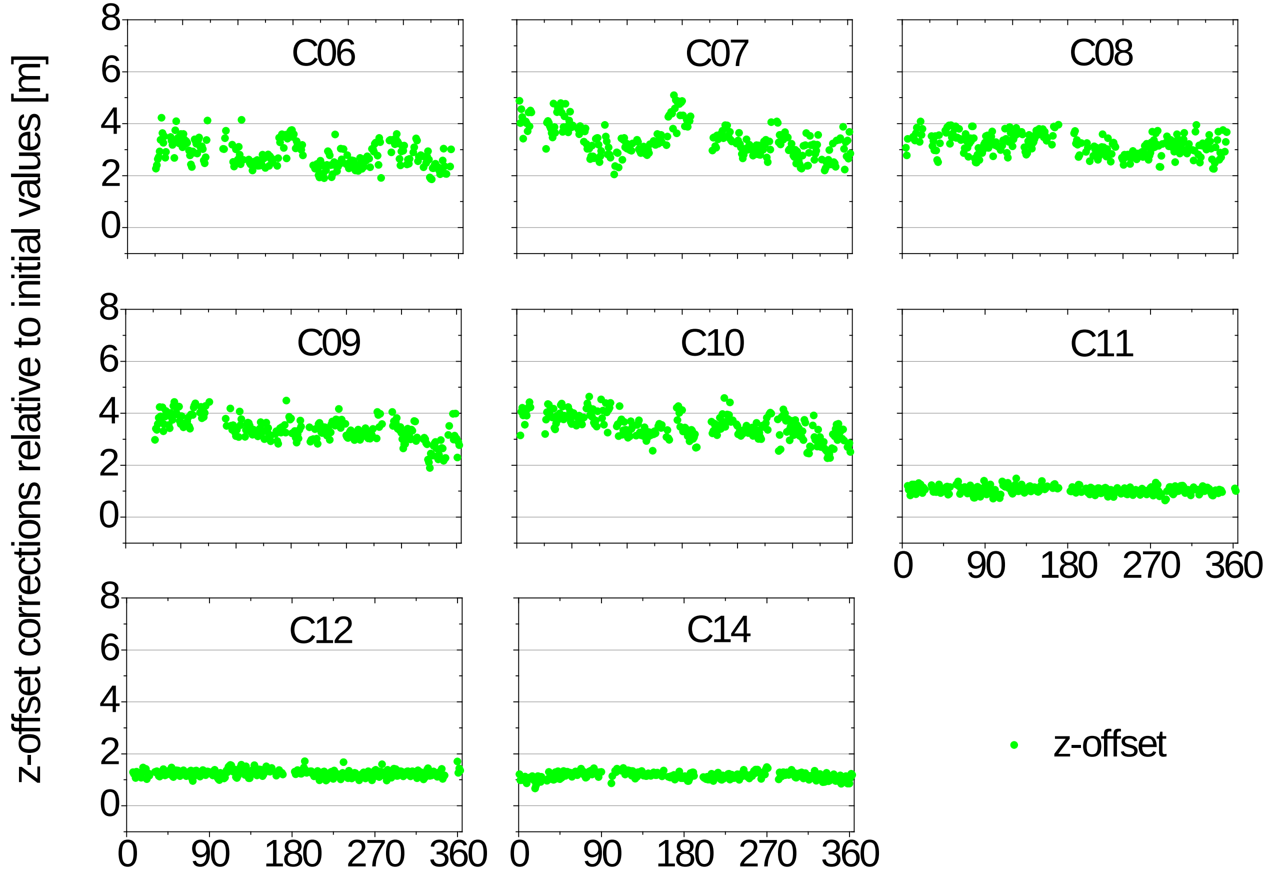
Impact of different SRP model – ECOM1



The rangers of **x-offset** variation related to beta angle are **0.2-0.4 m (IGSO)** and **0.1-0.2 m (MEO).** The rangers of **y-offset** variation are **0.2m (IGSO)** and **0.1 (MEO).**

3.1 PCOs estimation for BeiDou-2

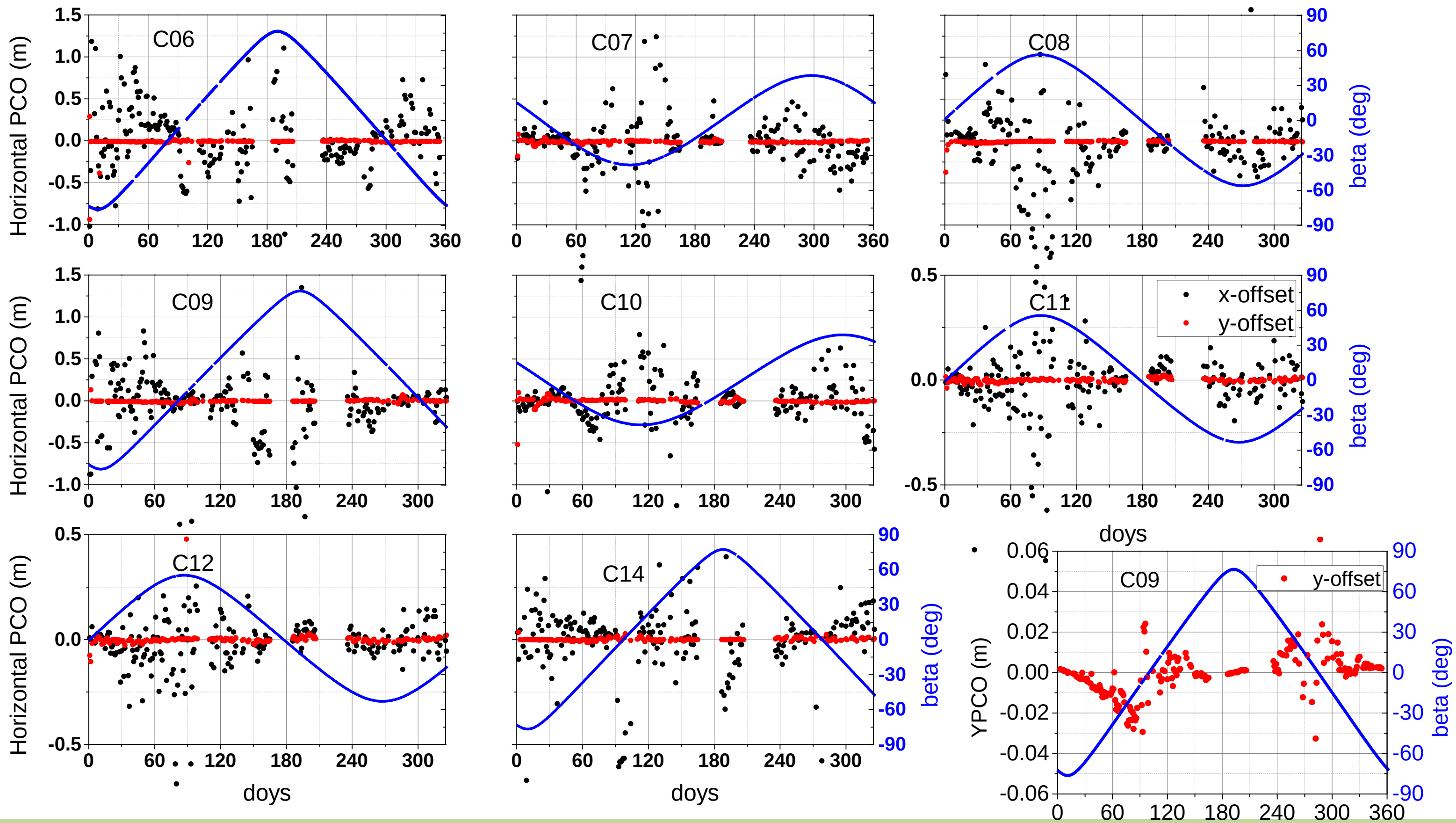
Impact of different SRP model – ECOM1



The rangers of z-offset variation are **2 m** and **0.5 m** for IGSO and MEO respectively.

3.1 PCOs estimation for BeiDou-2

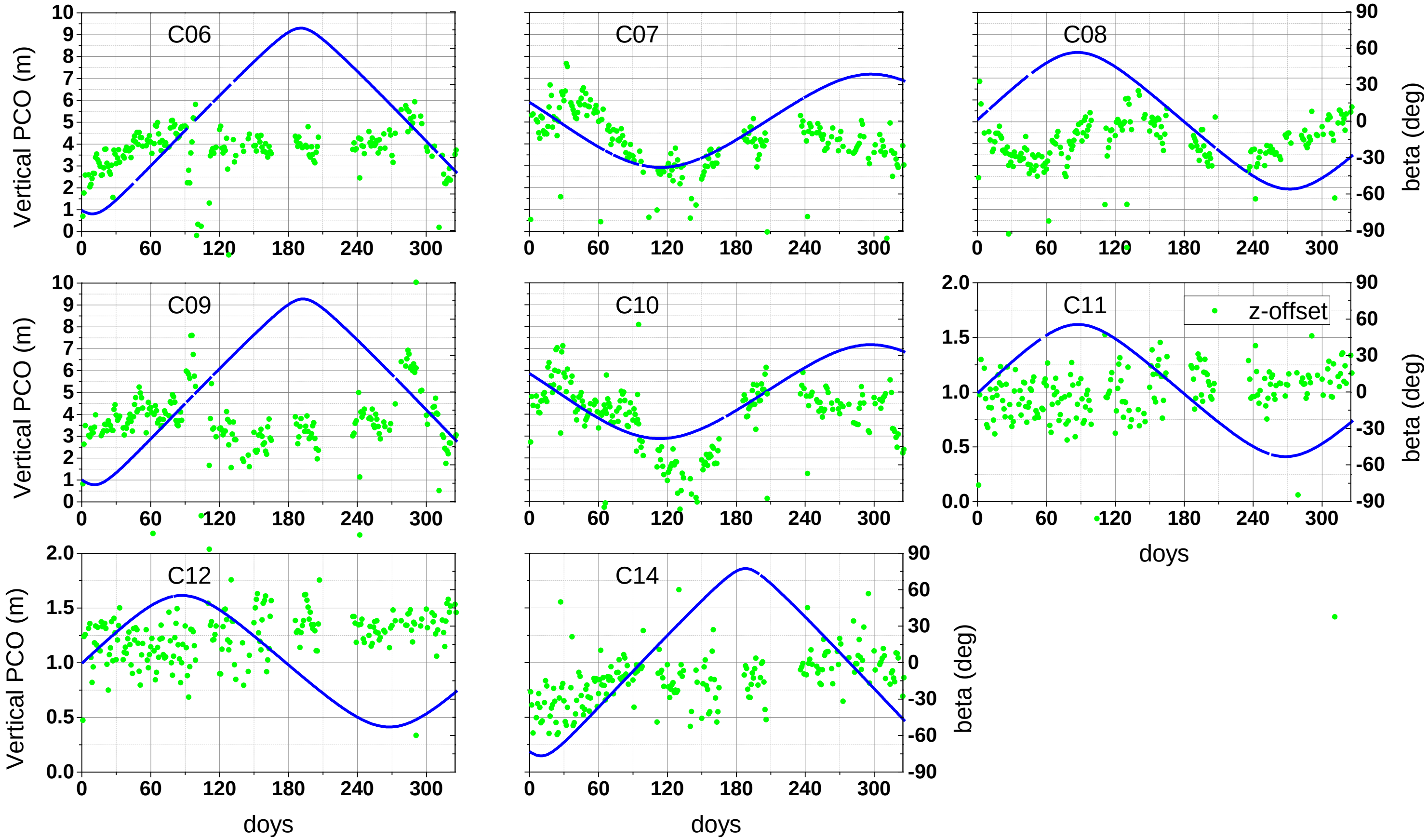
Impact of different SRP models – ECOM2 (Arnold et al., 2015)



The x-offset variation are **1** and **0.5 m** for IGSO and MEO respectively. For the same types of satellites (IGSO or MEO), **the larger beta angle, the larger scatters**, which is similar to Galileo PCOs (Steigenberge et al., 2016). The y-offset variation is **4cm.**

3.1 PCOs estimation for BeiDou-2

Impact of different SRP model – ECOM2 (Arnold et al., 2015)



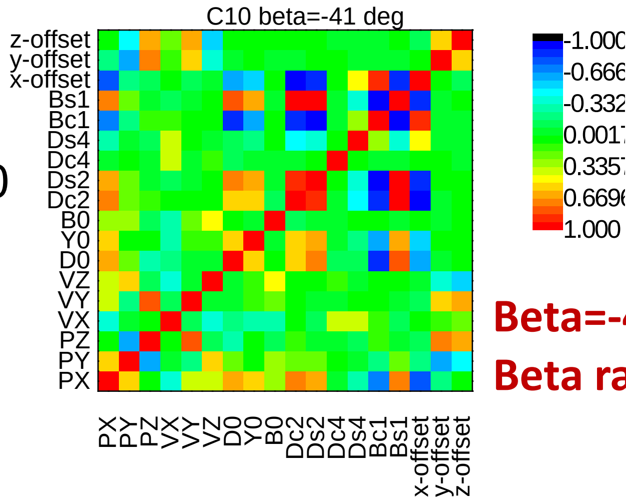
Z-offset had a significant systematic variation of **5 m** for IGSO (C06-C10), **1 m** for MEO.

3.1 PCOs estimation for BeiDou-2

Correlation analysis between orbital and PCO parameters by using ECOM2

(a)

C10

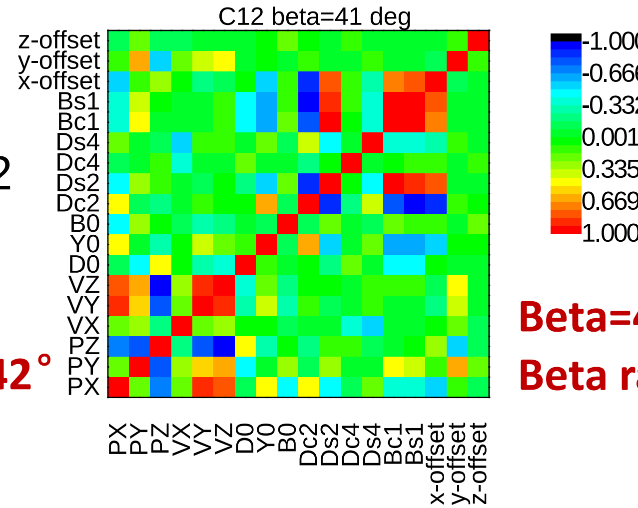


Beta=-41 deg

Beta range: ±42°

(b)

C12

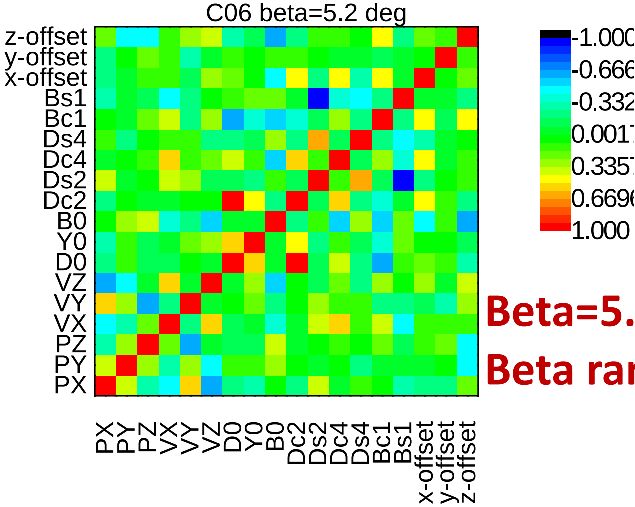


Beta=41 deg

Beta range: ±42°

(c)

C06



Beta=5.2 deg

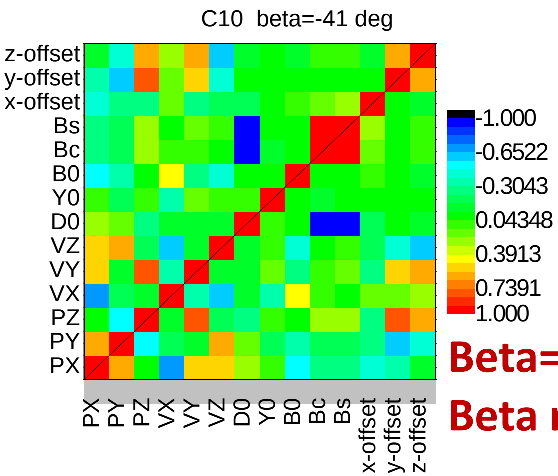
Beta range: ±77°

Higher beta:
x-offset and **Dc2, Ds2, Bc1, Bs1 (higher correlations)**;
y-offset has a **weaker correlation**;

3.1 PCOs estimation for BeiDou-2

Correlation analysis between orbital and PCO parameters by using ECOM1

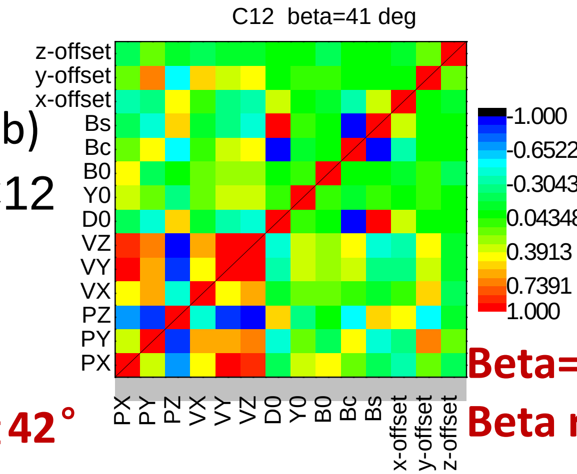
(a)
C10



Beta=-41 deg

Beta range: ±42°

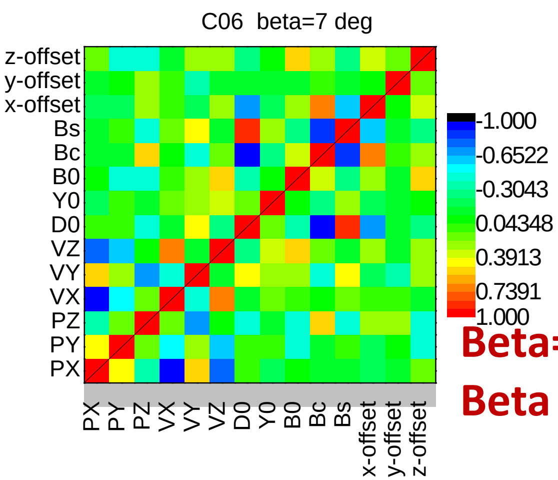
(b)
C12



Beta=41 deg

Beta range: ±42°

(c)
C06



Beta=7 deg

Beta range: ±77°

Higher beta:
y-offset and **positions and velocities (higher correlation);**
x-offset has a **weaker correlation** than that of **ECOM2**.

ECOM1 had smaller variations of x-offset and z-offset series than that of ECOM2, and **ECOM1** was chose to estimate PCOs in the next.

3.1 PCOs estimation for BeiDou-2

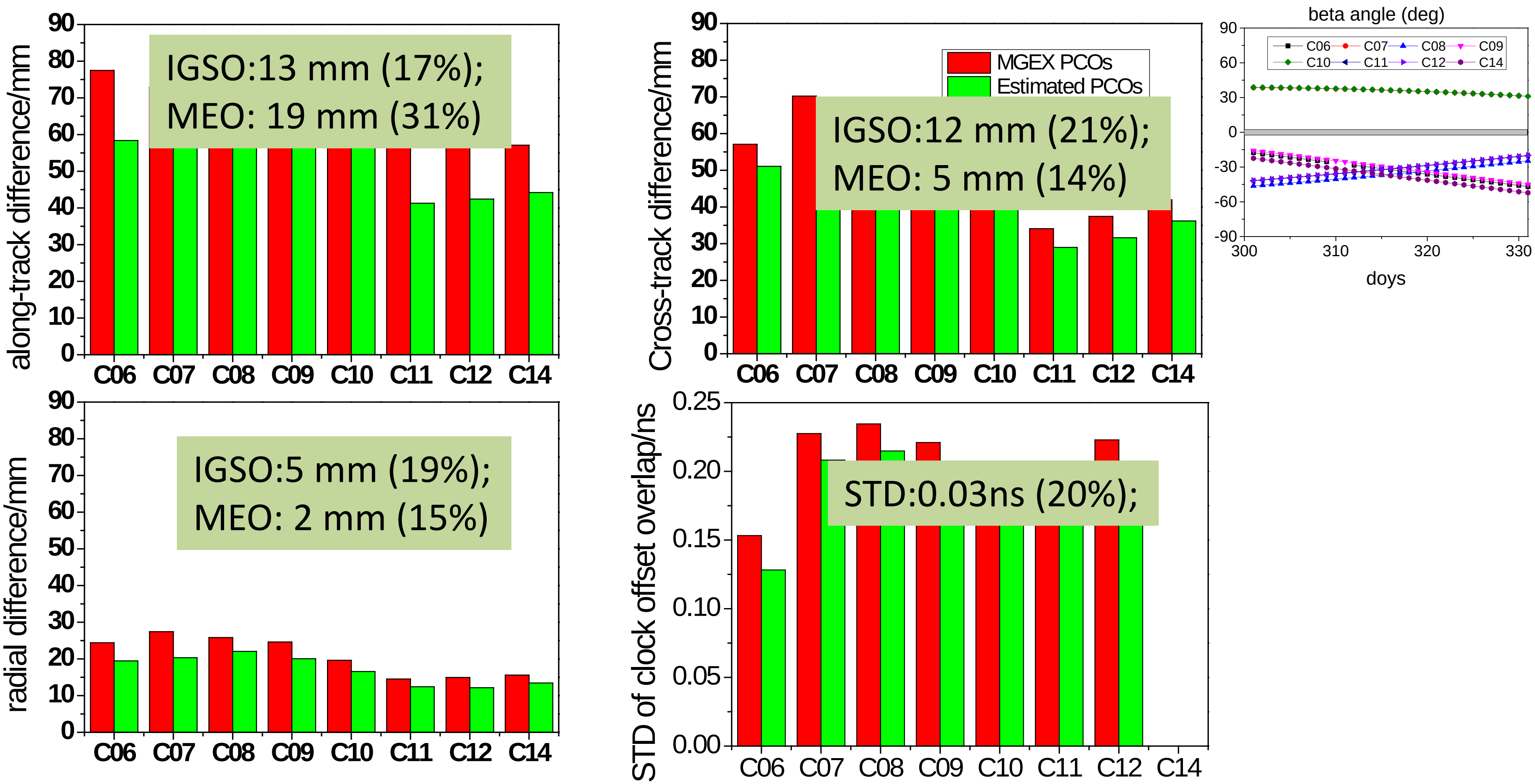
Estimations of PCOs from CHA, ESOC and WHU (unit: mm)

	CHA			ESOC			WHU		
PRN	x-offset	y-offset	z-offset	x-offset	y-offset	z-offset	x-offset	y-offset	z-offset
C06	554.17	0.00	**3894.01**	549.00	0.00	**3049.00**	586.40	0.00	**2513.70**
C07	554.17	0.00	**4469.97**	549.00	0.00	**3236.70**	586.40	0.00	**2721.90**
C08	554.17	0.00	**4283.91**	549.00	0.00	**3842.60**	586.40	0.00	**3440.00**
C09	554.17	0.00	**4469.40**	549.00	0.00	**3973.60**	586.40	0.00	**3551.90**
C10	554.17	0.00	**4571.83**	549.00	0.00	**3882.10**	586.40	0.00	**4087.00**
C11	572.00	0.00	2143.34	549.00	0.00	2069.50	575.00	0.00	1990.70
C12	572.00	0.00	2348.76	549.00	0.00	2313.50	575.00	0.00	2249.10
C14	572.00	0.00	2256.46	549.00	0.00	2311.70	575.00	0.00	2144.30

3.2 Validation of PCOs estimation for BeiDou-2

orbit and clock offset overlapping precision

Time period: 2015,301-331

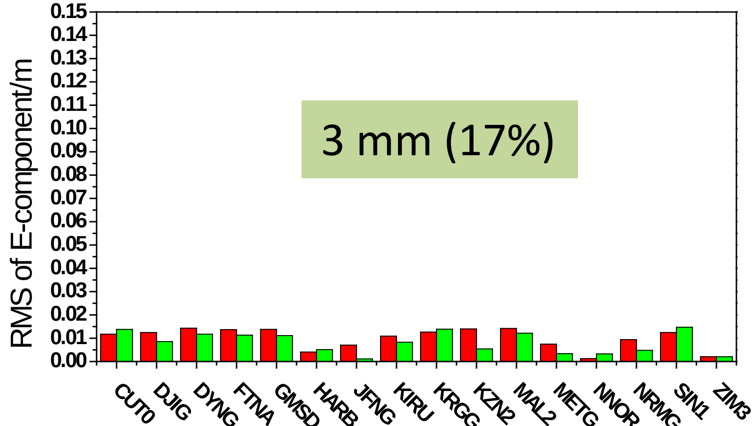


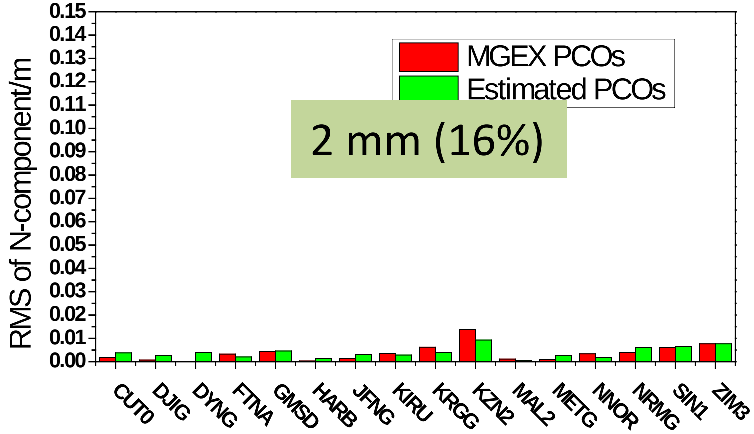
The influence of the reference clock data was subtracted by differencing with the reference clock offset series, and C14 was chose as the reference satellite.

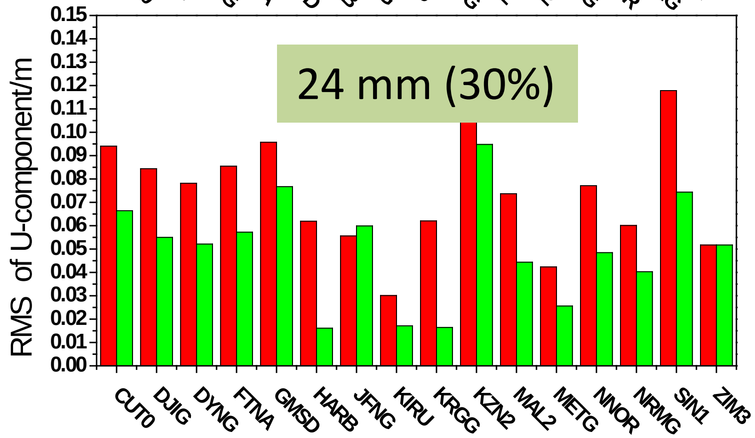
3.2 Validation of PCOs estimation for BeiDou-2

coordinate estimation

Static solution, Only C06-C12,C14 were used; 2015,301-331;
16 stations selected randomly.







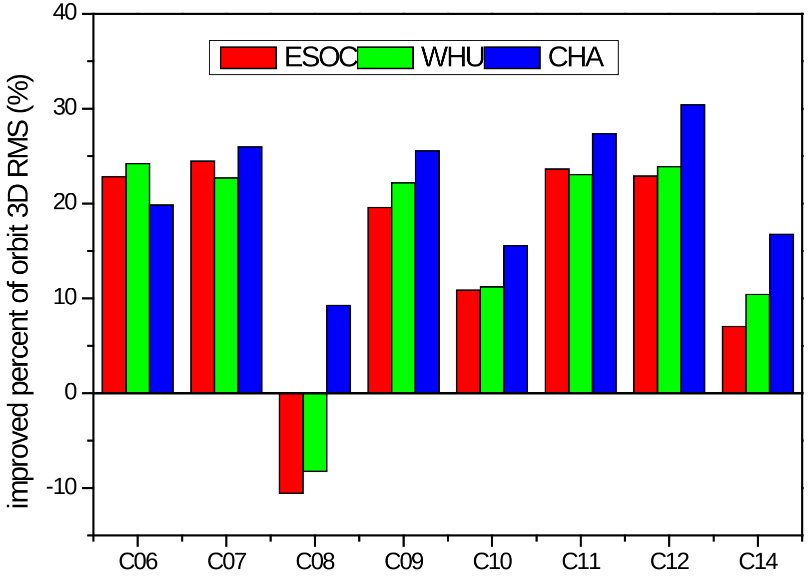
Average RMSs of coordinates in the ENU components (unit: m)

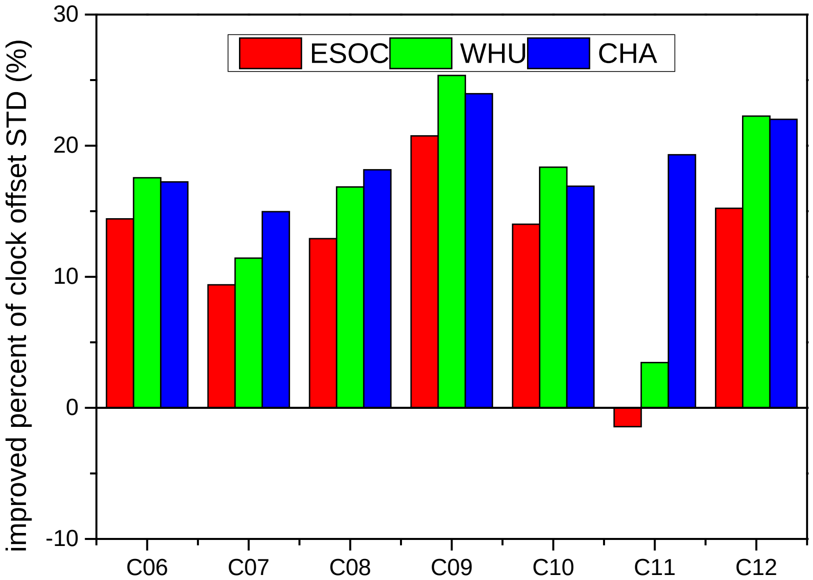
	E	N	U
MGEX PCOs	0.017	0.008	**0.080**
Estimated PCOs	0.014	0.006	**0.056**

3.2 Validation of PCOs estimation for BeiDou-2

Comparisons with the ESOC and WHU results – orbit and clock offset

ESOC: PCOs and PVs; (Dilssner et al. 2014)
WHU: PCOs and PVs; (Guo, 2014)
CHA: PCOs and set PVs=0;





Improved percent of the precision of orbit and clock offset overlap when compared with the MGEX model

	ESOC	WHU	CHA
3D RMS of orbit	15.09%	16.17%	21.34%
STD of clock offset	12.18%	16.46%	18.93%

3.2 Validation of PCOs estimation for BeiDou-2

Comparisons with the ESOC and WHU results – coordinate estimation

The average RMSs in ENU components, the unit is m

	RMS_E	RMS_N	RMS_U
MGEX	0.017	0.008	0.080
CHA	0.015	0.006	0.056
ESOC	0.017	0.013	0.057
WHU	0.016	0.013	0.056

Although there are differences in the orbit and clock precision by using the different phase center correction models, but the **impact** on the coordinate estimation **is small** for ESOC, WHU, and CHA models.

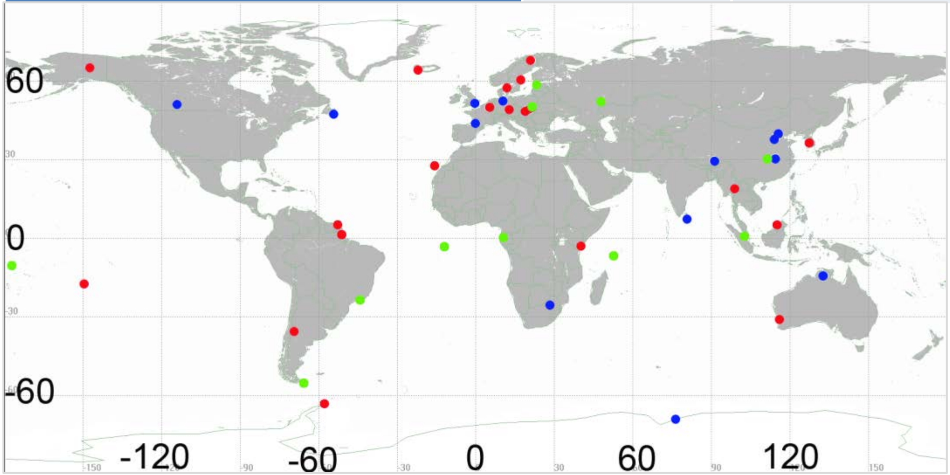
4. preliminary PCOs estimation for BeiDou-3 B1 & B3 combination

4.1 BeiDou-3 satellites

Status of BeiDou-3 satellites.

http://mgex.igs.org/IGS_MGEX_Status_BDS.php

Common Name	SVN	COSPAR ID	PRN	Launch date
BeiDou-3 M1	C201	2017-069A	C19	2017.11.05
BeiDou-3 M2	C202	2017-069B	C20	2017.11.05
BeiDou-3 M7	C203	2018-003A	C27	2018.01.11
BeiDou-3 M8	C204	2018-003B	C28	2018.01.11
BeiDou-3 M3	C205	2018-018A	C22	2018.02.12
BeiDou-3 M4	C206	2018-018B	C21	2018.02.12
BeiDou-3 M9	C207	2018-029A	C29	2018.03.29
BeiDou-3 M10	C208	2018-029B	C30	2018.03.29

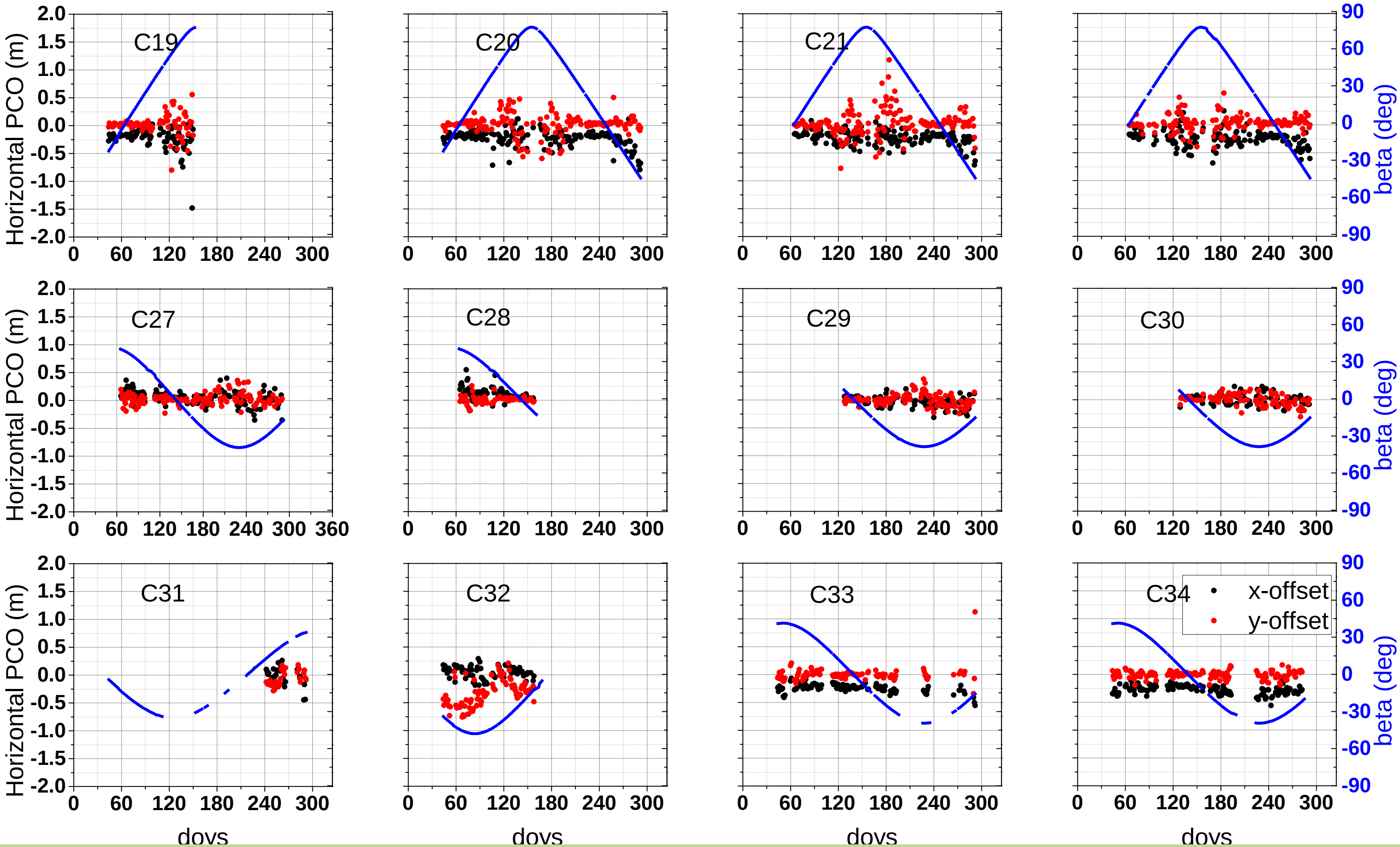


BeiDou-2: 24 (14 MGEX + 10 iGMAS)
BeiDou-3: 13 (3 MGEX + 10 iGMAS)
BeiDou-3e: 13 (3 MGEX + 10 iGMAS)

Distribution of the stations used for POD. **Blue** are BeiDou-3 and BeiDou-2 stations, and **green** are BeiDou-2 stations, **red** are GPS-only stations.

4.2 PCOs estimation for BeiDou-3

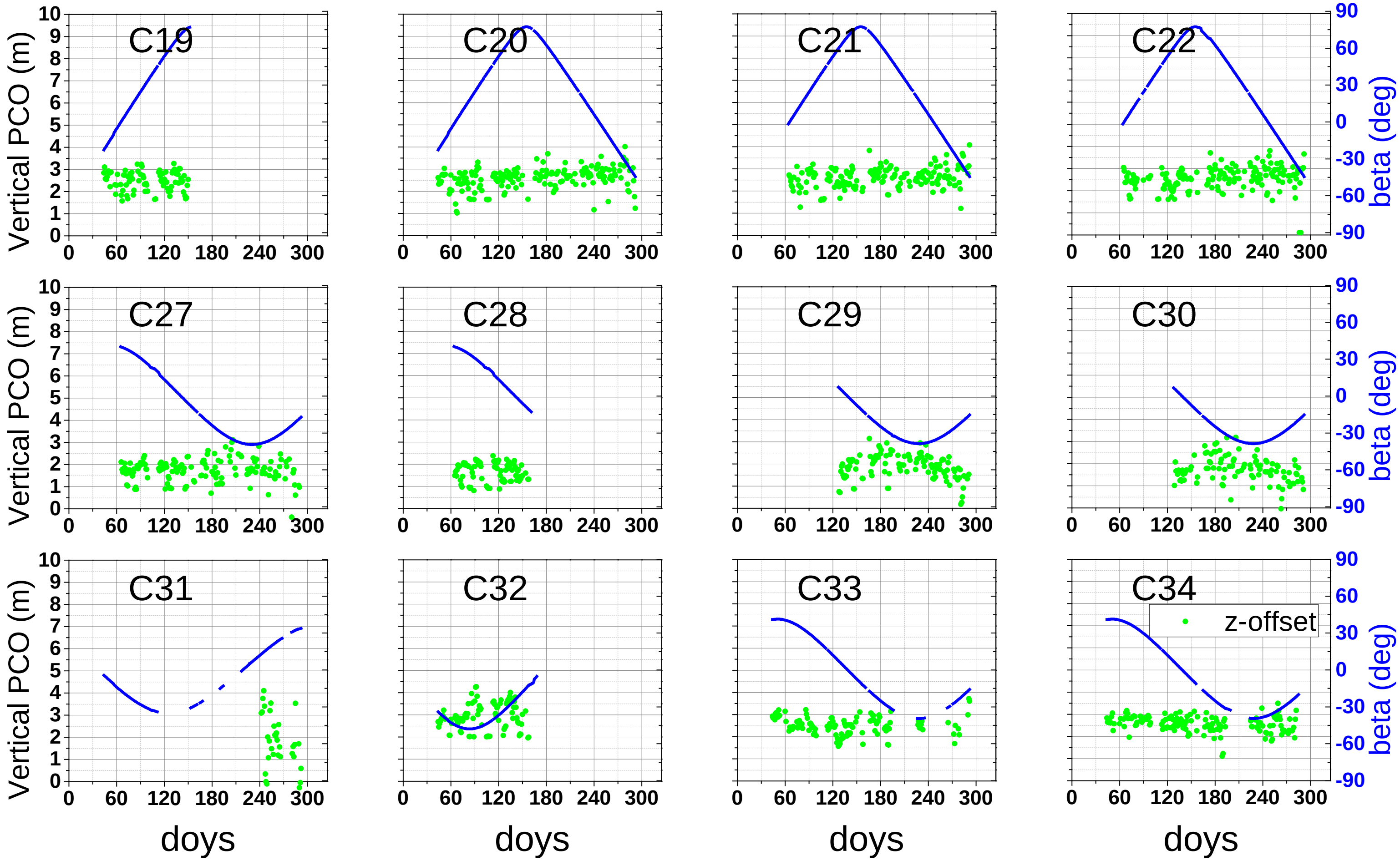
B1I & B3I combination



ECOM1 was used to estimate PCOs, a loose constraint of 10 m for all PCOs (x-offset, y-offset, and z-offset); time period is from 044 to 292, 2018.

4.2 PCOs estimation for BeiDou-3

B1I & B3I combination



4.2 PCOs estimation for BeiDou-3

B1I & B3I combination

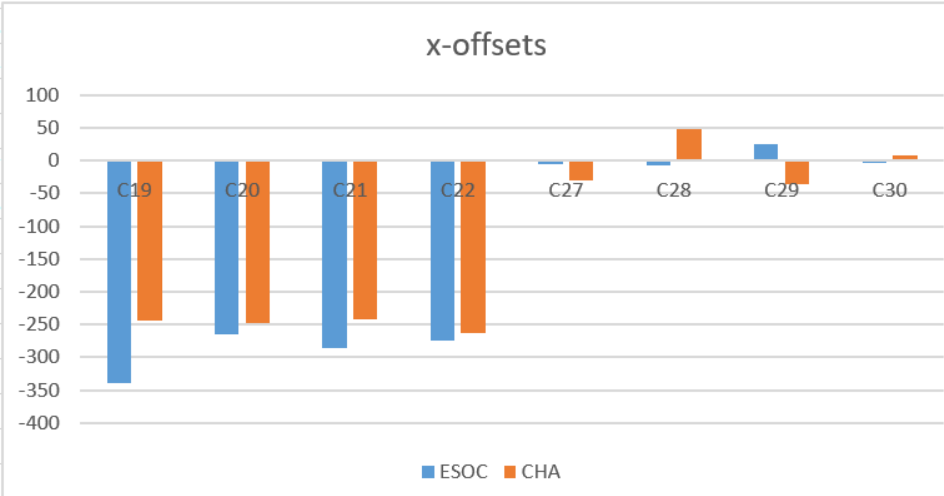
PRN	x-offset	y-offset	z-offset
C06	602.6	-27.1	5386.2
C07	557.6	1.1	4982.2
C08	581.3	-46.6	6232.6
C09	574.4	-70.4	5662.8
C10	588.5	-24.6	5336.4
C11	584.7	14.1	2539.7
C12	601.1	16.3	2764.0
C13	590.5	-18.9	4247.8
C14	596.1	-3.2	2600.3
C19	-244.2	-21.4	2399.2
C20	-247.5	-16.3	2545.4
C21	-242.8	-28.6	2520.0
C22	-262.3	-4.4	2474.6
C27	29.4	-18.0	1699.1
C28	47.7	-2.8	1648.4
C29	-35.9	-19.8	1880.1
C30	8.0	-12.0	1655.8
C31	-37.1	-124.4	1657.9
C32	45.1	-341.2	2831.6
C33	-244.8	-9.3	2486.6
C34	-260.4	-0.7	2610.2

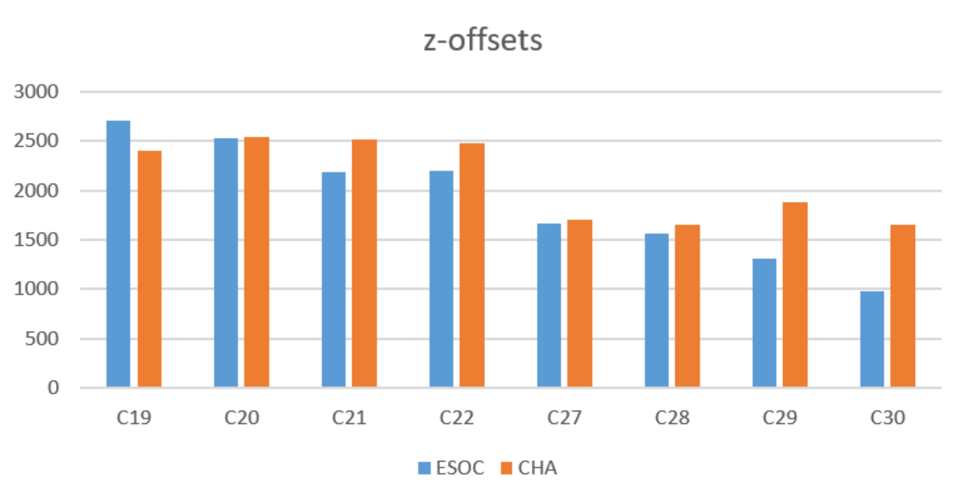
ESOC(Dilssner et al. 2014; IGS workshop 2018)

PRN	x-offset	y-offset	z-offset
C06	545.0	0.0	3509.5
C07	545.0	0.0	4121.2
C08	545.0	0.0	4710.2
C09	545.0	0.0	5029.8
C10	545.0	0.0	4935.1
C11	545.0	0.0	2214.2
C12	545.0	0.0	2401.9
C13	——	——	——
C14	545.0	0.0	2450.2
C19	-338.6	-55.3	2708.4
C20	-264.9	19.4	2521.9
C21	-285.4	39.2	2178.9
C22	-273.8	73.2	2200.0
C27	-5.4	64.0	1659.8
C28	-6.8	53.1	1558.8
C29	25.3	35.2	1307.7
C30	-3.3	52.7	975.9

4.2 PCOs estimation for BeiDou-3

B1I & B3I combination



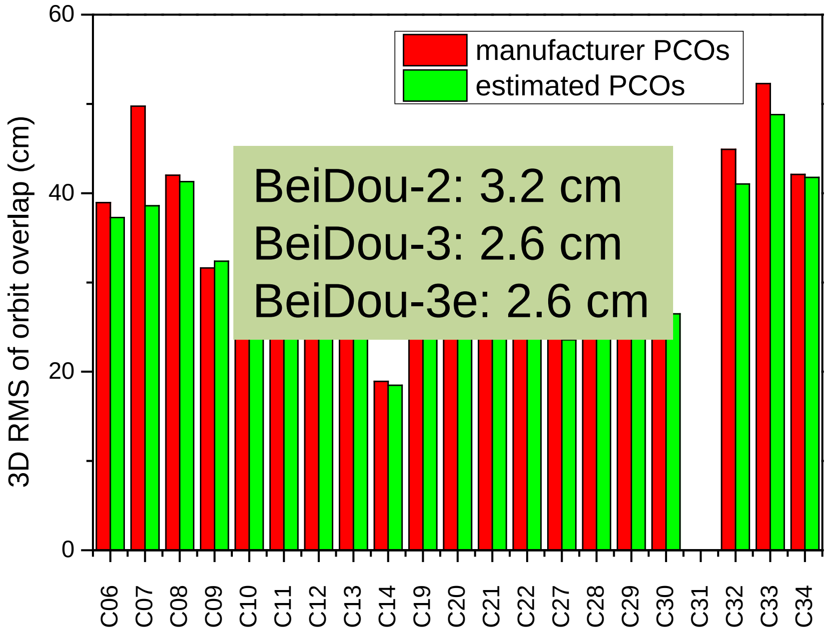


It seems to match pretty well with the ESOC, under the limited amount of tracking data available (13 stations) so far;
X-offset: 1~9 cm;
Z-offset: 4~34 cm (except for C29 and C30)

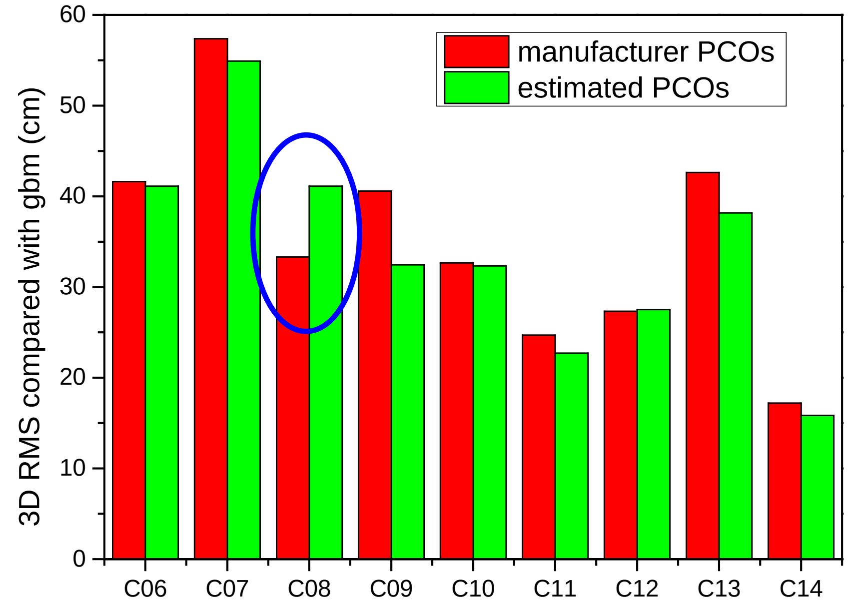
4.3 Validation of PCOs estimation for BeiDou-3

Orbit precision

Compared with overlap



Compared with GBM



Improvement of orbit overlap (cm)

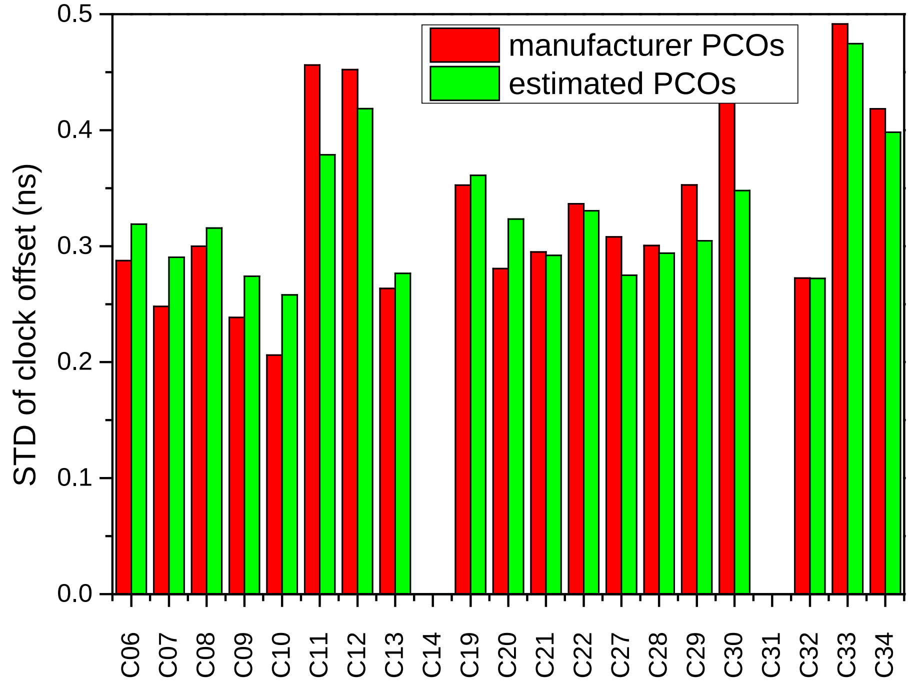
type	Average	median
BeiDou-2	3.2	2.4
BeiDou-3	2.6	2.7
BeiDou-3e	2.6	2.0

Improvement of accuracy compared with GBM final product(cm)

type	Average	median
BeiDou-2	1.2	2.3

4.3 Validation of PCOs estimation for BeiDou-3

Clock offset precision



For **IGSO** satellites, the STD values of clock offset **overlap are increased**;

For most of **MEO** satellites, the STD values have an average improvement of **0.03** ns, except for **C19** and **C20**.

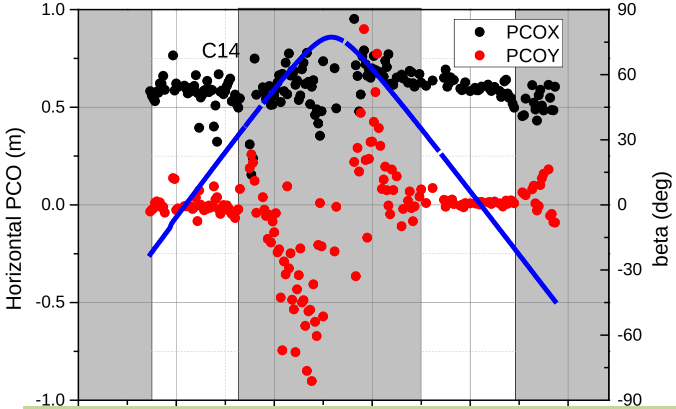
Lack of stations limited the accuracy of POD.

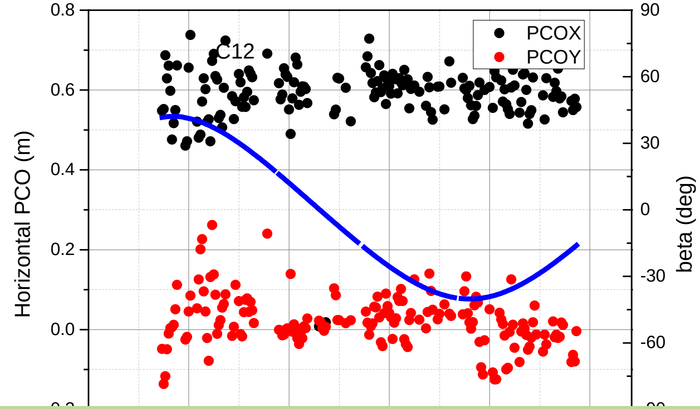
5. Summary

- Estimated PCOs can improve the precision of orbit and clock offset;
- Estimated PCOs can improve the accuracy of BDS-only PPP, especially in U-component;
- The three estimated PCOs (ESOC, WHU, CHA) have small difference on the coordinate results;
- Preliminary PCOs of BeiDou-3 can slightly improve the precision of orbit and clock offset. However, the improvement is limited by the lack of stations. Higher accurate PCOs will be achieved by long time data processing in the future.

6. Outlook

(1) SRP model





ECOM1 is suffer from stretch shape of satellite body, like Galileo and BeiDou; higher beta angle caused larger scatters of x-offset and y-offset. Thus, a priori box-wing model is more necessary for higher beta satellites to get a more stable series of x-offset and y-offset.

(2) IGSO z-offset

BeiDou-2 MEO and IGSO have the same shape of body, the main difference is the geometry of the observations from the earth. The maximum nadir angles are 9° and 13° for the IGSO and MEO, the smaller the maximum nadir angle means the higher correlation between z-offset and satellite clock offset, also some extra correlations such as PZ,VY, VZ.

Adding the LEO data to enlarge the nadir angle is a capable way to improve the accuracy of IGSO PCOs, especially for z-offset.

Thanks for your attention!