Estimating a set of IFCBs to make IGS ionospheric-free clock product compatible with various triple-frequency PPP models

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Lin Pan

Wuhan University

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<u>Lin Pan</u>, Xiaohong Zhang, Jingnan Liu

School of Geodesy and Geomatics, Wuhan University

1. A newly emerging situation

BDS-2: B1/B2/B3

BDS-3/3S: B1/B3/B1C/B2a/B2b

Galileo: E1/E5A/E5B/E5(A+B)/E6

GPS Block IIF: L1/L2/L5

GLONASS-K/GLONASS-M: G1/G2/G3

QZSS: L1/L2/L5

Benefit: formation of inter-frequency combinations with good features; increased measurement redundancy
Challenge : satellite clock inconsistency

Montenbruck et al. (2010) identified the presence of time-, signal- and satellite-dependent line biases in carrier phase observations.

2. IGS satellite clocks

Code and carrier-phase observations:

$$P_i = \rho + cdt_r - cdt + I \cdot \gamma_i + T + d_{r,i} + \boxed{d_i}$$

$$\Phi_i = \rho + cdt_r - cdt - I \cdot \gamma_i + T + N_i + b_{r,i} + b_{c,i} + \boxed{b_{v,i}}$$

IGS satellite clocks (L1/L2 ionospheric-free (IF) satellite clocks):

$$cdt_{IF,12} = cdt - \boxed{(a_{12,1} \cdot d_1 + a_{12,2} \cdot d_2) - (a_{12,1} \cdot b_{v,1} + a_{12,2} \cdot b_{v,2})}$$

L1/L5 IF satellite clocks:

$$cdt_{IF,15} = cdt - \boxed{(a_{15,1} \cdot d_1 + a_{15,2} \cdot d_5) - (a_{15,1} \cdot b_{v,1} + a_{15,2} \cdot b_{v,5})}$$

$$= cdt_{IF,12} + \mathrm{IFCB}$$

Kept consistent with Inter-Frequency Clock Bias (IFCB)

$$a_{12,1} = f_1^2 / (f_1^2 - f_2^2) \qquad a_{12,2} = -f_2^2 / (f_1^2 - f_2^2)$$

$$a_{15,1} = f_1^2 / (f_1^2 - f_5^2) \qquad a_{15,2} = -f_5^2 / (f_1^2 - f_5^2)$$

3. Mathematical conversion formula among various IFCBs

IF-PPP1： L1/L2 IF+L1/L5 IF

IF-PPP2： L1/L2/L5 IF (infinite number of combs. with only two conditions)

UC-PPP： L1 UC+L2 UC+L5 UC

The current IFCB estimation approach should be modified from time to time

IFCB(IF-PPP1) IFCB(IF-PPP2) IFCB(UC-PPP)

Relationship?

Satellite clock determination (Guo and Geng 2017): IF-PPP1 & UC-PPP

Least-squares adjustment (Montenbruck et al. 2012): IF-PPP1

Epoch-differenced (ED) strategy (Li et al. 2016): IF-PPP1

3. Mathematical conversion formula among various IFCBs

IFCB (IF-PPP1: L1/L2 IF+L1/L5 IF)

Introduction of IFCB:

$$cdt_{IF,15} = cdt_{IF,12} + \beta_{IF,15} + \delta_{IF,15}$$

Code-specific IFCB (CIFCB):

$$\beta_{IF,15} = \left(a_{12,1} \cdot d_1 + a_{12,2} \cdot d_2\right) - \left(a_{15,1} \cdot d_1 + a_{15,2} \cdot d_5\right)$$

$$= -a_{12,2} \cdot \mathrm{DCB}(P_1, P_2) + a_{15,2} \cdot \mathrm{DCB}(P_1, P_5)$$

$$\begin{cases} \mathrm{DCB}(P_1, P_2) = d_1 - d_2 \\ \mathrm{DCB}(P_1, P_5) = d_1 - d_5 \end{cases}$$

Phase-specific IFCB (PIFCB):

$$\delta_{IF,15} = \left(a_{12,1} \cdot b_{v,1} + a_{12,2} \cdot b_{v,2}\right) - \left(a_{15,1} \cdot b_{v,1} + a_{15,2} \cdot b_{v,5}\right)$$

3. Mathematical conversion formula among various IFCBs

IFCB (IF-PPP1: L1/L2 IF+L1/L5 IF)

Triple-frequency GFIF (Geometry-Free and Ionospheric-Free) carrier phase combinations:

$$\begin{aligned}\text{GFIF} &= (a_{12,1}\cdot\Phi_1 + a_{12,2}\cdot\Phi_2) - (a_{15,1}\cdot\Phi_1 + a_{15,2}\cdot\Phi_5)\\ &= (a_{12,1}\cdot b_{v,1} + a_{12,2}\cdot b_{v,2}) - (a_{15,1}\cdot b_{v,1} + a_{15,2}\cdot b_{v,5}) + N_{\text{GFIF}} + b_{r,\text{GFIF}} + b_{c,\text{GFIF}}\\ &= \delta_{IF,15} + N_{\text{GFIF}} + b_{r,\text{GFIF}} + b_{c,\text{GFIF}}\end{aligned}$$

$$\begin{cases} N_{\text{GFIF}} = (a_{12,1}\cdot N_1 + a_{12,2}\cdot N_2) - (a_{15,1}\cdot N_1 + a_{15,2}\cdot N_5)\\ b_{r,\text{GFIF}} = (a_{12,1}\cdot b_{r,1} + a_{12,2}\cdot b_{r,2}) - (a_{15,1}\cdot b_{r,1} + a_{15,2}\cdot b_{r,5})\\ b_{c,\text{GFIF}} = (a_{12,1}\cdot b_{c,1} + a_{12,2}\cdot b_{c,2}) - (a_{15,1}\cdot b_{c,1} + a_{15,2}\cdot b_{c,5}) \end{cases}$$

PIFCB observation equation

$$\delta_{IF,15} = \text{GFIF} - (N_{\text{GFIF}} + b_{r,\text{GFIF}} + b_{c,\text{GFIF}})$$

3. Mathematical conversion formula among various IFCBs

IFCB (IF-PPP1: L1/L2 IF+L1/L5 IF)

Estimation process of PIFCB:

$$\Delta\delta_{IF,15,r}^{s}(t,t-1)=\mathrm{GFIF}_r^s(t)-\mathrm{GFIF}_r^s(t-1)$$

Eliminating stable terms with ED processing

$$\Delta\delta_{IF,15}^{s}(t,t-1)=\left[\sum_{r=1}^{n(t,t-1)}\Delta\delta_{IF,15,r}^{s}(t,t-1)\cdot w_r^s(t,t-1)\right]\Big/\left[\sum_{r=1}^{n(t,t-1)}w_r^s(t,t-1)\right]$$

$$w_r^s(t,t-1)=\begin{cases}\sin el_r^s(t,t-1) & el_r^s(t,t-1)<40^\circ\\ 1 & el_r^s(t,t-1)\geq 40^\circ\end{cases}$$

A weighted average of solutions over the entire network

$$\delta_{IF,15}^{s}(t)=\delta_{IF,15}^{s}(t_0)+\sum_{j=t_0+1}^{t}\Delta\delta_{IF,15}^{s}(j,j-1)$$

The PIFCB at each epoch can be obtained with an accumulation

Li et al. (2016): ED strategy

3. Mathematical conversion formula among various IFCBs

IFCB (UC-PPP: L1 UC+L2 UC+L5 UC)

$$\begin{cases} cdt_{UC,1} = cdt_{IF,12} + \beta_{UC,1} + \delta_{UC,1} \\ cdt_{UC,2} = cdt_{IF,12} + \beta_{UC,2} + \delta_{UC,2} \\ cdt_{UC,5} = cdt_{IF,12} + \beta_{UC,5} + \delta_{UC,5} \end{cases}$$

L1/L2 IF satellite clocks are converted into uncombined (UC) satellite clocks with estimated L1, L2 and L5 UC CIFCB and PIFCB

$$\begin{cases} \beta_{UC,1} = -a_{12,2} \cdot \mathrm{DCB}(P_1, P_2) \\ \beta_{UC,2} = a_{12,1} \cdot \mathrm{DCB}(P_1, P_2) \\ \beta_{UC,5} = -a_{12,2} \cdot \mathrm{DCB}(P_1, P_2) + \mathrm{DCB}(P_1, P_5) \\ \delta_{UC,1} = 0 \\ \delta_{UC,2} = 0 \end{cases}$$

DCB is used to compute the L1, L2 and L5 UC CIFCB

Both L1 and L2 UC PIFCB equal to 0, while an extra consideration of L5 UC PIFCB is necessary

3. Mathematical conversion formula among various IFCBs

IFCB (UC-PPP: L1 UC+L2 UC+L5 UC)

$$\begin{cases} \overline{P}_1 = \rho + cdt_{r,E} + I_E + T + [-(a_{12,1} - a_{12,2}) \cdot b_{v,1} - 2 \cdot a_{12,2} \cdot b_{v,2}] \\ \overline{P}_2 = \rho + cdt_{r,E} + I_E \cdot \gamma_2 + T + [-2 \cdot a_{12,1} \cdot b_{v,1} + (a_{12,1} - a_{12,2}) \cdot b_{v,2}] \\ \overline{P}_5 = \rho + cdt_{r,E} + I_E \cdot \gamma_5 + T + g_{UC-PPP} + [a_{12,2} \cdot (\gamma_2 + \gamma_5) \cdot b_{v,1} + a_{12,2} \cdot (1 - \gamma_5) \cdot b_{v,2} + \delta_{UC,5}] \\ \overline{\Phi}_1 = \rho + cdt_{r,E} - I_E + T + N_{1,E} \\ \overline{\Phi}_2 = \rho + cdt_{r,E} - I_E \cdot \gamma_2 + T + N_{2,E} \\ \overline{\Phi}_5 = \rho + cdt_{r,E} - I_E \cdot \gamma_5 + T + N_{5,E} + \delta_{UC,5} \end{cases}$$

$$\begin{cases} cdt_{r,E} = cdt_r + a_{12,1} \cdot d_{r,1} + a_{12,2} \cdot d_{r,2} \\ I_E = I - a_{12,2} \cdot (d_{r,2} - d_{r,1}) + a_{12,2} \cdot (b_{v,2} - b_{v,1}) \\ g_{UC-PPP} = (-\gamma_5 \cdot a_{12,2} - a_{12,1}) \cdot d_{r,1} - a_{12,2} \cdot (1 - \gamma_5) \cdot d_{r,2} + d_{r,5} \\ N_{1,E} = N_1 + b_{r,1} + b_{c,1} - d_1 - (a_{12,1} - a_{12,2}) \cdot d_{r,1} - 2 \cdot a_{12,2} \cdot d_{r,2} \\ N_{2,E} = N_2 + b_{r,2} + b_{c,2} - d_2 - (a_{12,1} - \gamma_2 \cdot a_{12,2}) \cdot d_{r,1} - a_{12,2} \cdot (1 + \gamma_2) \cdot d_{r,2} \\ N_{5,E} = N_5 + b_{r,5} + b_{c,5} - d_5 - (a_{12,1} - \gamma_5 \cdot a_{12,2}) \cdot d_{r,1} - a_{12,2} \cdot (1 + \gamma_5) \cdot d_{r,2} \end{cases}$$

The UC triple-frequency PPP observation equations after applying the L1, L2 and L5 UC satellite clocks

3. Mathematical conversion formula among various IFCBs

IFCB (UC-PPP: L1 UC+L2 UC+L5 UC)

$$\delta_{UC,5} = a_{12,1} \cdot (1-\gamma_5/\gamma_2) \cdot b_{v,1} - a_{12,2} \cdot (\gamma_5 - 1) \cdot b_{v,2} - b_{v,5}$$

Formulating the L5 UC PIFCB

L1/L5 IF PIFCB:

$$\begin{aligned}\delta_{IF,15} &= \left(a_{12,1} \cdot b_{v,1} + a_{12,2} \cdot b_{v,2}\right) - \left(a_{15,1} \cdot b_{v,1} + a_{15,2} \cdot b_{v,5}\right) \\ &= (a_{12,1} - a_{15,1}) \cdot b_{v,1} + a_{12,2} \cdot b_{v,2} - a_{15,2} \cdot b_{v,5}\end{aligned}$$

$$\delta_{UC,5} \cdot a_{15,2} = (a_{12,1} - a_{15,1}) \cdot b_{v,1} + a_{12,2} \cdot b_{v,2} - a_{15,2} \cdot b_{v,5} = \delta_{IF,15}$$

$$\delta_{UC,5} = \delta_{IF,15} / a_{15,2}$$

The estimated L1/L5 IF PIFCB can be converted into L5 UC PIFCB

$$a_{12,1} = f_1^2/(f_1^2 - f_2^2) \qquad a_{12,2} = -f_2^2/(f_1^2 - f_2^2)$$

$$a_{15,1} = f_1^2/(f_1^2 - f_5^2) \qquad a_{15,2} = -f_5^2/(f_1^2 - f_5^2)$$

Coefficients for L1/L2 and L1/L5 IF combinations

3. Mathematical conversion formula among various IFCBs

IFCB (IF-PPP2: L1/L2/L5 IF)

$$\begin{cases} e_1 + e_2 + e_5 = 1 \\ e_1 + e_2 \cdot \gamma_2 + e_5 \cdot \gamma_5 = 0 \end{cases}$$

The combination coefficients fulfill these two conditions

$$cdt_{IF,125} = cdt - (e_1 \cdot d_1 + e_2 \cdot d_2 + e_5 \cdot d_5) - (e_1 \cdot b_{v,1} + e_2 \cdot b_{v,2} + e_5 \cdot b_{v,5})$$

Theoretical formula

$$cdt_{IF,125} = cdt_{IF,12} + \beta_{IF,125} + \delta_{IF,125}$$

Introduction of similar IFCBs

$$\begin{aligned} \beta_{IF,125} &= (a_{12,1} \cdot d_1 + a_{12,2} \cdot d_2) - (e_1 \cdot d_1 + e_2 \cdot d_2 + e_5 \cdot d_5) \\ &= (e_2 - a_{12,2}) \cdot \mathrm{DCB}(P_1, P_2) + e_5 \cdot \mathrm{DCB}(P_1, P_5) \end{aligned}$$

CIFCB

3. Mathematical conversion formula among various IFCBs

IFCB (IF-PPP2: L1/L2/L5 IF)

$$\delta_{IF,125} = \left(a_{12,1} \cdot b_{v,1} + a_{12,2} \cdot b_{v,2}\right) - \left(e_1 \cdot b_{v,1} + e_2 \cdot b_{v,2} + e_5 \cdot b_{v,5}\right)$$
$$= c_1 \cdot b_{v,1} + c_2 \cdot b_{v,2} + c_5 \cdot b_{v,5}$$

Formulating the L1/L2/L5 IF PIFCB

$$\begin{cases} c_1 = a_{12,1} - e_1 \\ c_2 = a_{12,2} - e_2 \\ c_5 = -e_5 \end{cases} \qquad \begin{cases} c_1 + c_2 + c_5 = 0 \\ c_1 + c_2 \cdot \gamma_2 + c_5 \cdot \gamma_5 = 0 \end{cases} \qquad \begin{cases} c_1 = \dfrac{\gamma_5 - \gamma_2}{\gamma_2 - 1} \cdot c_5 \\ c_2 = \dfrac{1 - \gamma_5}{\gamma_2 - 1} \cdot c_5 \end{cases}$$

Three combination coefficients in L1/L2/L5 IF PIFCB

$$\delta_{IF,125} = \frac{\gamma_5 - \gamma_2}{\gamma_2 - 1} \cdot c_5 \cdot b_{v,1} + \frac{1 - \gamma_5}{\gamma_2 - 1} \cdot c_5 \cdot b_{v,2} + c_5 \cdot b_{v,5}$$
$$= \left(\frac{\gamma_5 - \gamma_2}{\gamma_2 - 1} \cdot b_{v,1} + \frac{1 - \gamma_5}{\gamma_2 - 1} \cdot b_{v,2} + b_{v,5}\right) \cdot c_5$$
$$= \left(\frac{\gamma_5 - \gamma_2}{\gamma_2 - 1} \cdot b_{v,1} + \frac{1 - \gamma_5}{\gamma_2 - 1} \cdot b_{v,2} + b_{v,5}\right) \cdot (-e_5)$$

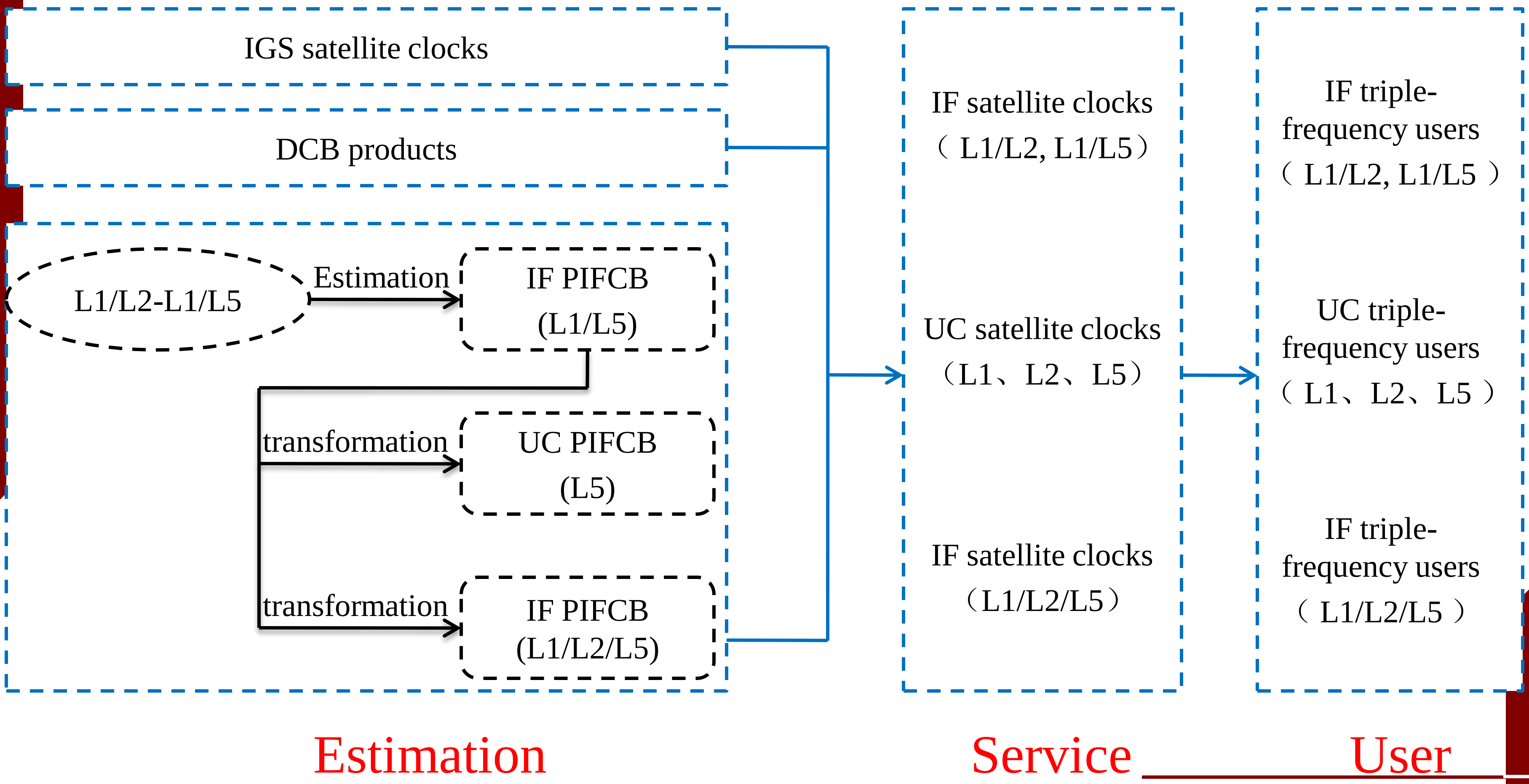
Various L1/L2/L5 IF PIFCBs are proportionally correlated with each other

$$\delta_{IF,125} = \delta_{IF,15} \cdot e_5 / a_{15,2}$$

The estimated L1/L5 IF PIFCB can also be converted into L1/L2/L5 IF PIFCB

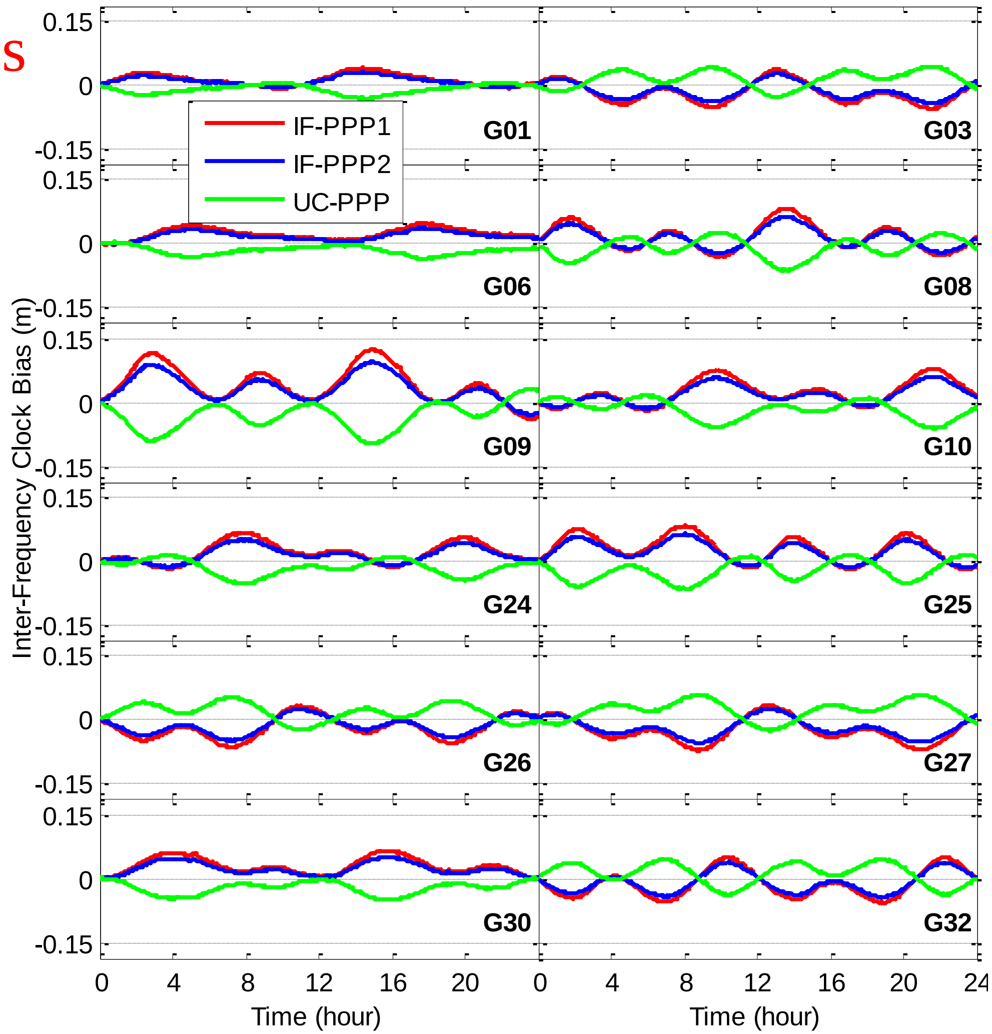
3. Mathematical conversion formula among various IFCBs

Satellite clocks for various triple-frequency PPP models



4. Results

PIFCB estimates



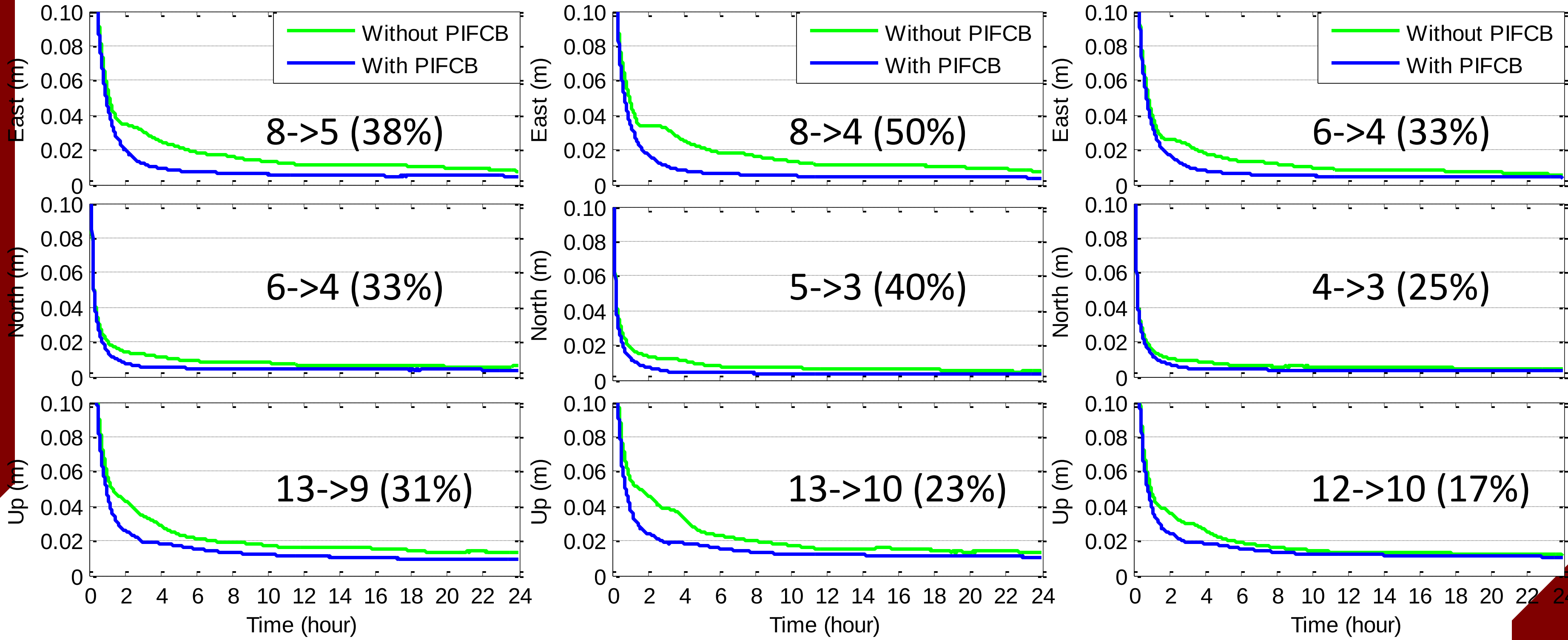
Amplitude:

4–16 cm

PIFCB estimates for UC-PPP, IF-PPP2 and IF-PPP1 on April 8, 2017

4. Results

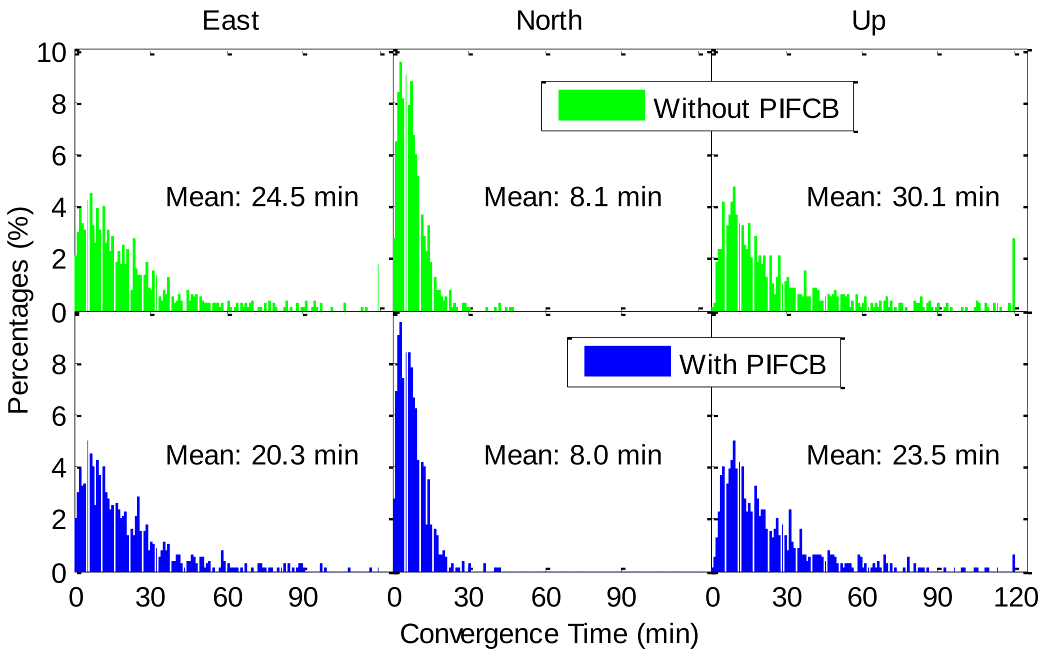
Positioning accuracy



Epoch-wise RMS values of UC-PPP (left), IF-PPP2 (middle) and IF-PPP1 (right) positioning errors without and with PIFCB consideration for different observational lengths

4. Results

Convergence time



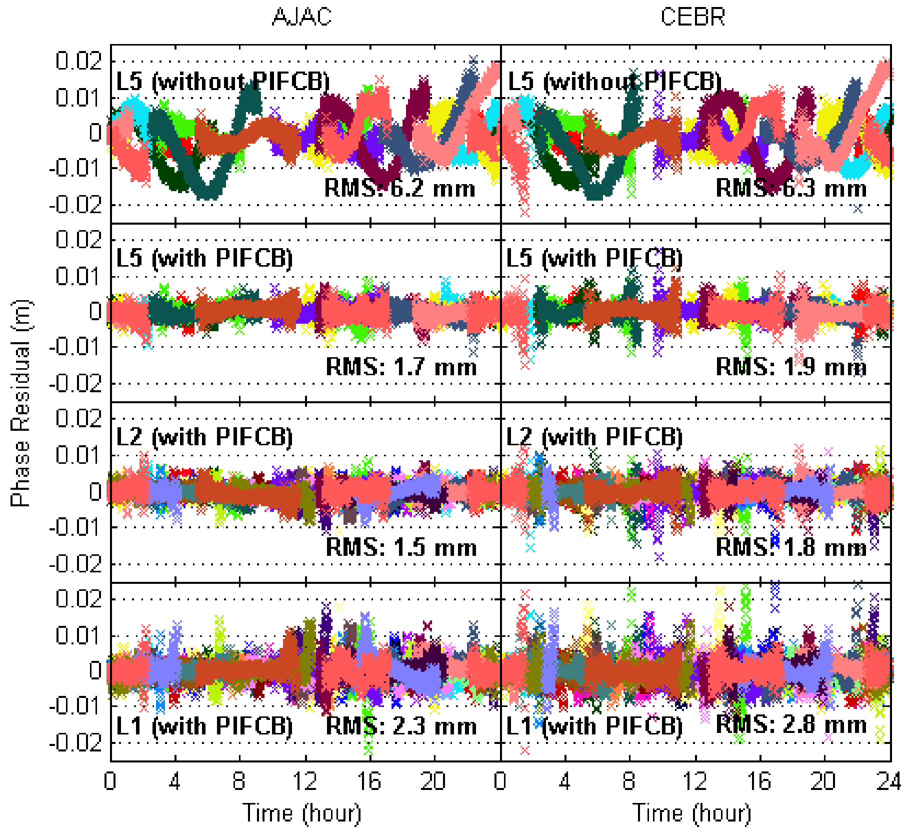
Improvement :

17%、1%、22%

Distribution of convergence time for 24-h UC-PPP solutions

4. Results

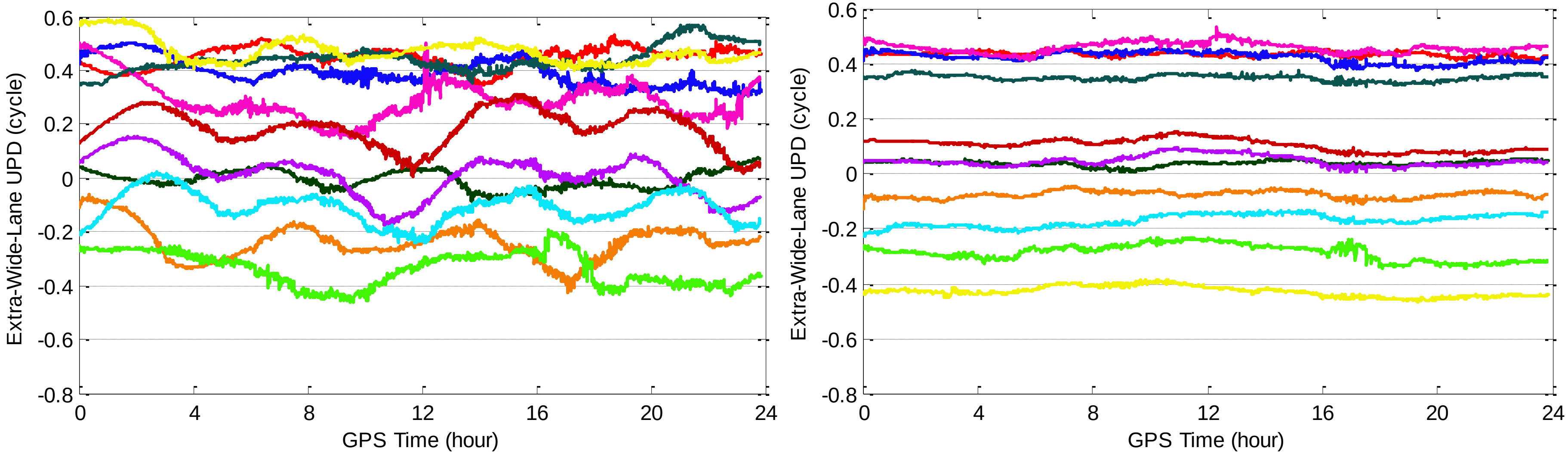
Phase observation residual



Phase observation residuals for UC triple-frequency PPP at stations AJAC and CEBR on April 2, 2017

4. Results

Extra-Wide-Lane (EWL) UPD estimates



Epoch-wise satellite EWL UPD estimates without (left) and with (right) PIFCB consideration on April 2, 2017

5. Conclusions

1. All the new-generation GNSS satellites are designed to transmit signals on three or more frequencies. The satellite clock consistency must be ensured.

2. The mathematical conversion formula among the PIFCBs of different triple-frequency PPP models is rigorously derived.

3. After applying the PIFCB corrections, the positioning accuracy, convergence time, phase observation residuals, and EWL UPD estimates are significantly improved.

Thank You for Your Attention!

More details refer to our recently published paper:
Pan L, et al. 2018. Journal of Geodesy.
doi:10.1007/s00190-018-1176-5